CP Violation in the B Meson System: The Belle Measurement of $\sin 2\phi_1$

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for the

BELLE Collaboration

The BELLE Collaboration

≈300 people from 49 Institutions in 11 Countries:

Australia, China, India, Korea, Japan, Philippines, Poland, Russia, Taiwan, Ukraine, and USA

Academia Sinica	Aomori University
Budker Inst. of Nuclear Physics	Chiba University
Chuo University	University of Cincinatti
Fukui University	GyeongSang National University
University of Hawaii	Institute of High Energy Physics
Institute of Single Crystal	Joint Crystal Collab. Group
Kanagawa University	KEK
Korea University	Krakow Inst. of Nuclear Physics
Kyoto University	Melbourne University
Mindanao State University	Nagasaki Inst. of App. Science
Nagoya University	Nara Women's University
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Nihon Dental College	Niigata University
Osaka University	Osaka City University
Princeton University	Saga University
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Seoul National University	Sugiyama Jyogakuin University
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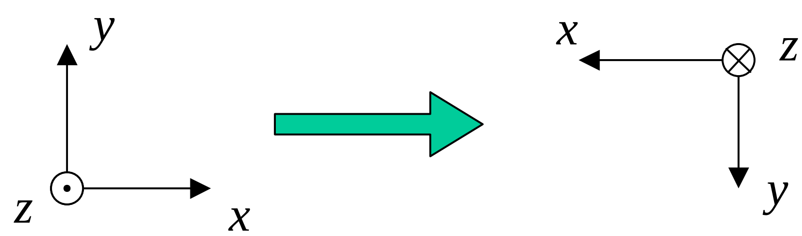
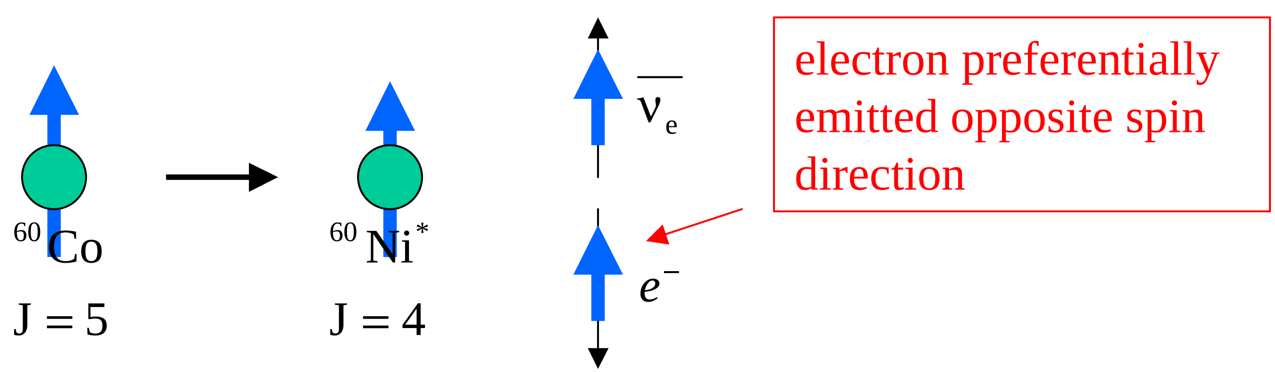
Parity Violation



- The “parity” operation transforms the universe into its mirror image (*goes from right-handed to left-handed*).
- Maxwell’s equations are totally parity invariant.
- BUT, in the 50’s huge parity violation was observed in weak decays…

β decay of polarized **Co:**



CP *(almost)* Conservation

- It was found that by applying the **C**[harge Conjugation] operation to all particles, the overall symmetry seemed to be restored (neutrinos are left-handed, anti-neutrinos are right-handed).
- This symmetry fit nicely into the current algebras, and later the gauge theories being used to describe weak interactions.
- Unfortunately, it wasn't *quite* exact…

CP Violation

- In 1964, Fitch, Cronin, *etal*, showed that physics is not *quite* invariant under the CP operation, essentially by proving that neutral kaons formed mass eigenstates

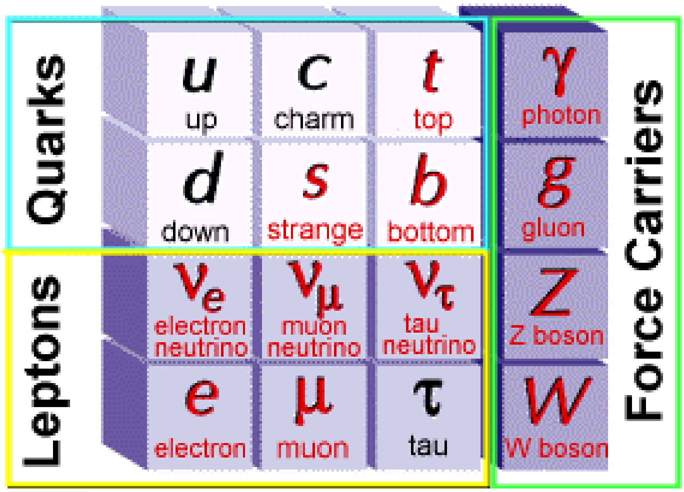
$$\left|K_{L,S}\right\rangle \equiv a_{L,S}\left|K^0\right\rangle + b_{L,S}\left|\overline{K^0}\right\rangle \quad \text{where} \quad \left|a_{L,S}\right| \neq \left|b_{L,S}\right|$$

- This generated great interest (not to mention a Nobel Prize), and has been studied in great detail ever since, but to date has only been conclusively observed in the kaon system.

$$\left(\left|a_{L,S}\right| - \left|b_{L,S}\right| \approx O(10^{-3})\right)$$

Weak Interactions in the Standard Model

- In the Standard Model, the fundamental particles are leptons and quarks



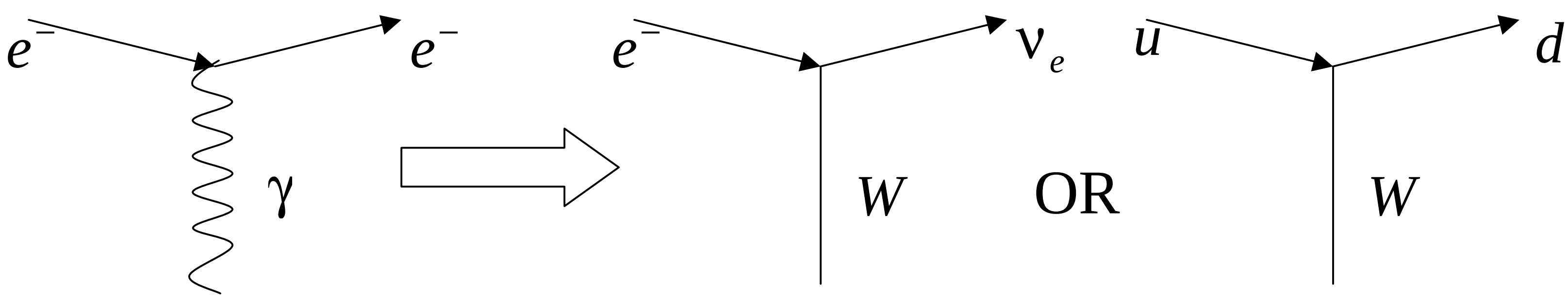
quarks combine as

$$qqq,\ \overline{qqq},\ \text{or}\ q\bar{q}$$

to form hadrons

leptons exist independently

- In this model, weak interactions are analogous to QED.



Quark Mixing

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

In the Standard Model, leptons can only transition *within* a generation (NOTE: probably not true!)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Although the rate is *suppressed*, quarks can transition *between* generations.

The CKM Matrix

- The weak quark eigenstates are related to the strong (or mass) eigenstates through a unitary transformation.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \Rightarrow \begin{pmatrix} u \\ \updownarrow \\ d' \end{pmatrix} \begin{pmatrix} c \\ \updownarrow \\ s' \end{pmatrix} \begin{pmatrix} t \\ \updownarrow \\ b' \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- The only straightforward way to *accommodate* CP violation in the SM is by means of an irreducible phase in this matrix (requires at least three generations, led to prediction of t and b quarks)

Wolfenstein Parameterization

The CKM matrix is an SU(3) transformation, which has four free parameters. Because of the scale of the elements, this is often represented with the "Wolfenstein Parameterization"

$$\cong \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

CP Violating phase

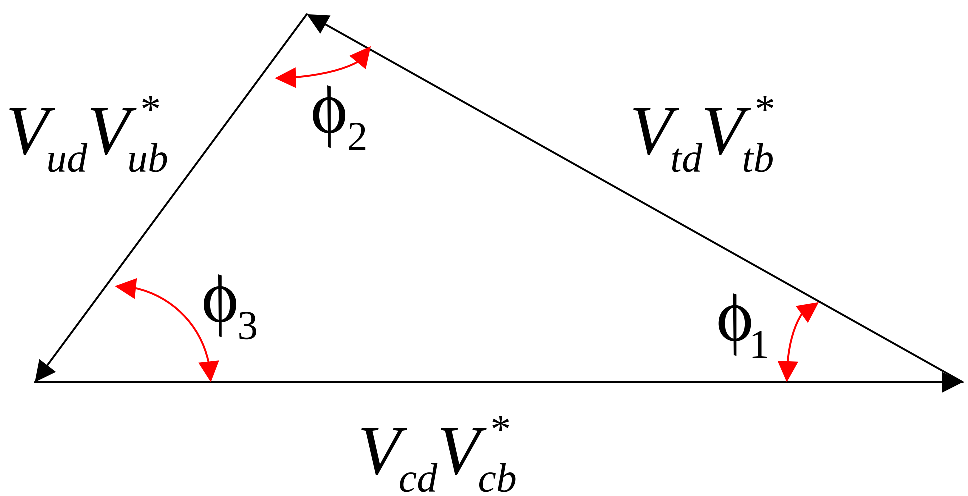
First two generations *almost* unitary.

"The" Unitarity Triangle

- Unitarity imposes several constraints on the matrix, but one...

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$$

Results in a triangle in the complex plane with sides of similar length $\left(\approx A\lambda^3\right)$, which appears the most interesting for study



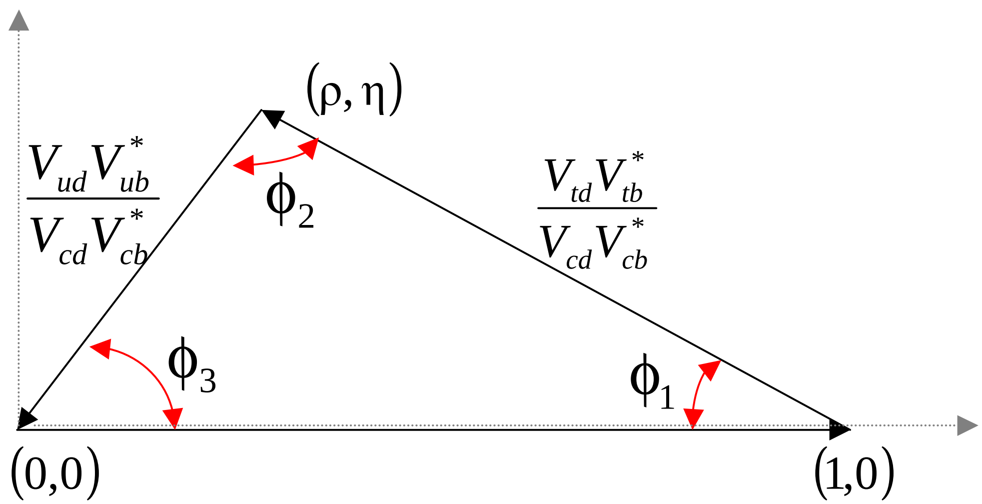
$$(\text{Note! in US}: \ \phi_1 \equiv \beta, \ \phi_2 \equiv \alpha, \ \phi_3 \equiv \gamma)$$

The ρ–η Plane

- Remembering the Wolfenstein Parameterization

$$\cong \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

we can divide through by the magnitude of the base….



CP violation is generally discussed in terms of this plane

Direct CP Violation

- CP Violation is manifests itself as a difference between the physics of matter and anti-matter

$$\Gamma(i \Rightarrow f) \neq \Gamma(\bar{i} \Rightarrow \bar{f})$$

- *Direct* CP Violation is the observation of a difference between two such decay rates; however, the amplitude for one process can in general be written

$$A = |A| e^{i\phi_w} e^{i\phi_s} \Rightarrow \bar{A} = |A| e^{-i\phi_w} e^{i\phi_s}$$

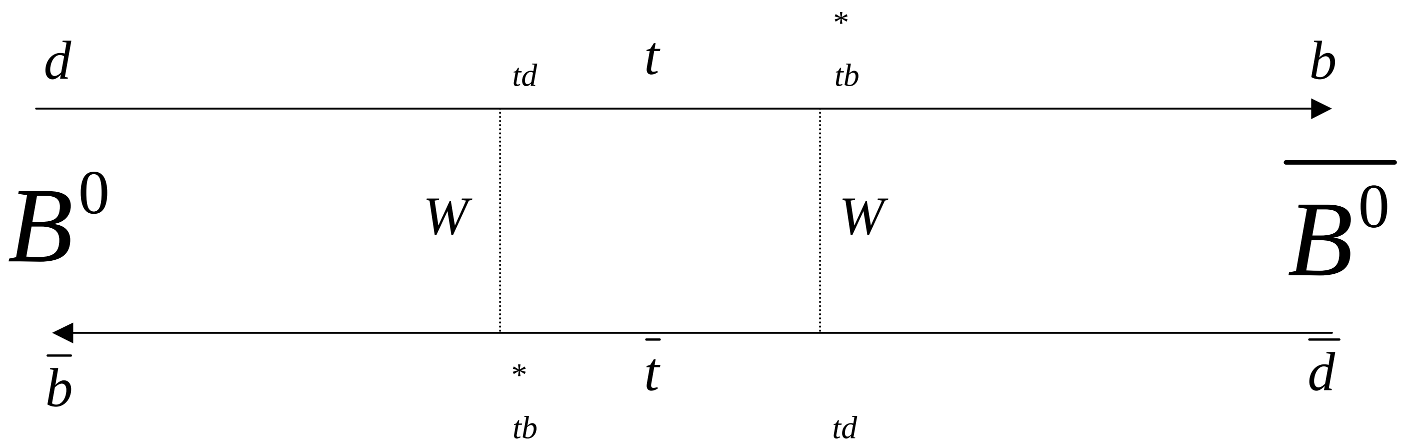
Weak phase changes sign   Strong phase does not

- Since the observed rate is only proportional to the amplitude, a difference would only be observed if there were an *interference* between two diagrams with different weak *and* strong phase.

$\Rightarrow$ Rare and hard to interpret

Indirect CP Violation

- Consider the case of B-mixing



$$\left|B^0(t)\right\rangle = e^{-i(m-i\Gamma)/2} \times \left[\cos\left(\tfrac{\Delta m t}{2}\right)\left|B^0\right\rangle + i\sin\left(\tfrac{\Delta m t}{2}\right)e^{-2i\phi_m}\left|\overline{B}^0\right\rangle\right]$$

Mixing phase $= \arg(V_{td}V_{tb}^{*}) = \phi_1$

Indirect CP Violation (cont'd)

- If both B and $\overline{B}$ can decay to the same *CP eigenstate* f, there will be an *interference*

$$
\begin{tikzcd}
B^0 \arrow[rr] \arrow[dr] & & f \\
& \overline{B}^0 \arrow[ur] &
\end{tikzcd}
$$

And the time-dependent decay probability will be

Difference between B mass eigenstates

$$P(t) = e^{-\Gamma|t|}\left[\left\{1 - \eta_{CP}\sin(\phi_M + \phi_D)\sin(\Delta m * t)\right\}\right]$$

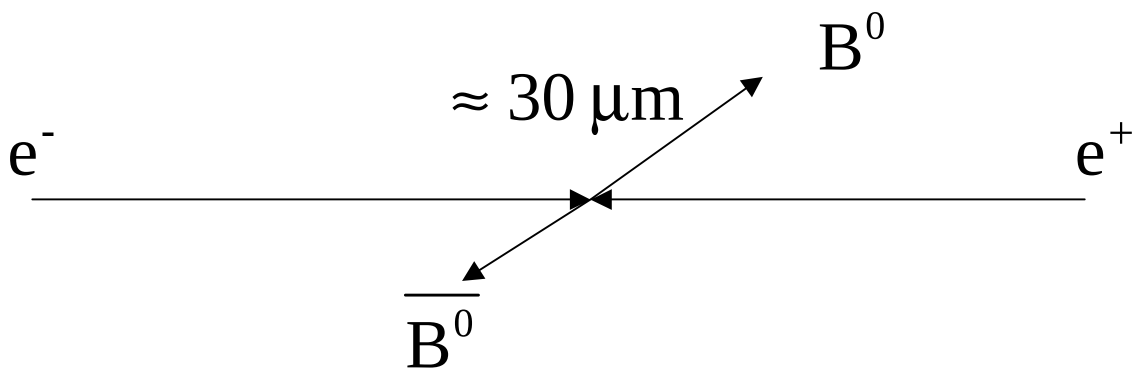
Decay phase

CP state of f

Mixing phase

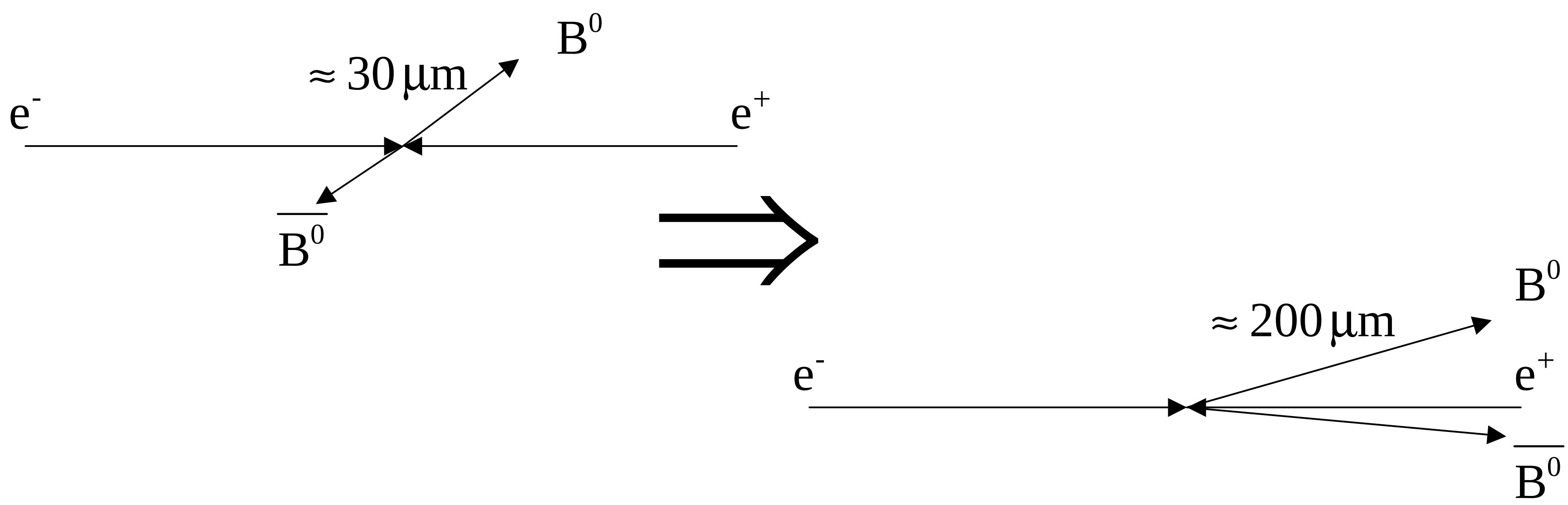
The Basic Idea

- We can create $B^0\overline{B^0}$ pairs at the $\Upsilon(4S)$ resonance.
- Even though both *B*'s are mixing, if we tag the decay of one of them, the other must be the CP conjugate *at that time*. We therefore measure the time dependent decay of one B relative to the time that the first one was tagged (EPR "paradox").
- PROBLEM: At the $\Upsilon(4S)$ resonance, B's only go about 30 μm in the center of mass, making it difficult to measure time-dependent mixing.



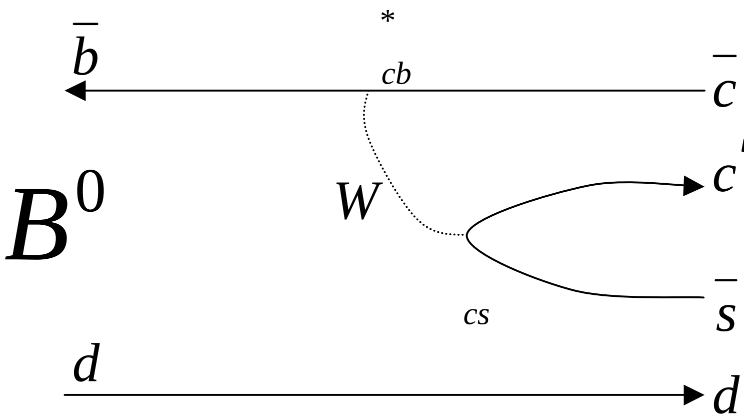
The Clever Trick

- If the collider is *asymmetric*, then the entire system is Lorentz boosted.
- In the Belle Experiment, 8 GeV e^-'s are collided with 3.5 GeV e^+'s so



- So now the time measurement becomes a *z* position measurement.

“Gold-Plated” Decay



$$J/\psi \quad (\psi \to e^+e^-, \mu^+\mu^-, \text{ etc})$$

Total state CP

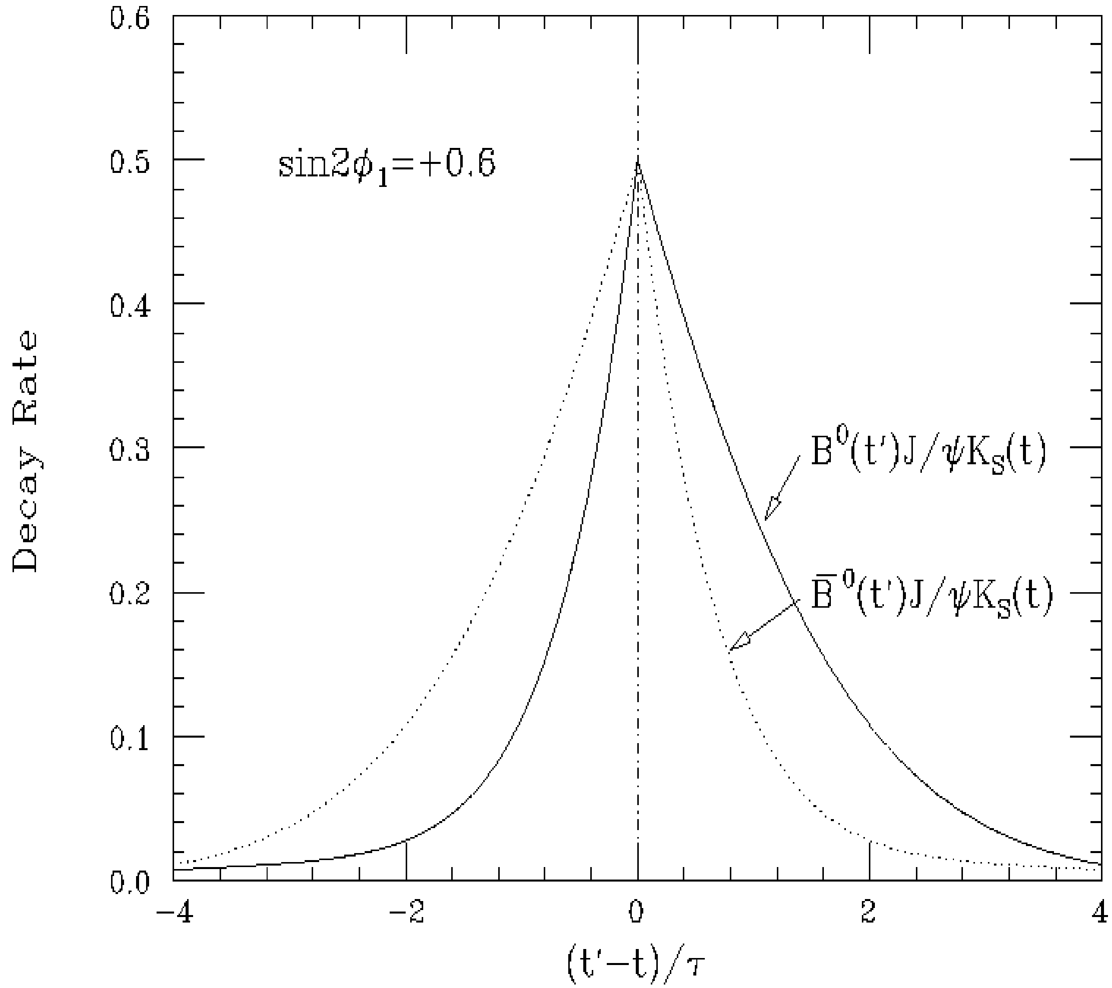
$$K_S(CP=-1), K_L(CP=+1)$$

$$\hookrightarrow \pi^+\pi^-, \pi^0\pi^0$$

$$\phi_D = \arg(V_{cs}V_{cb}^*) \approx 0$$

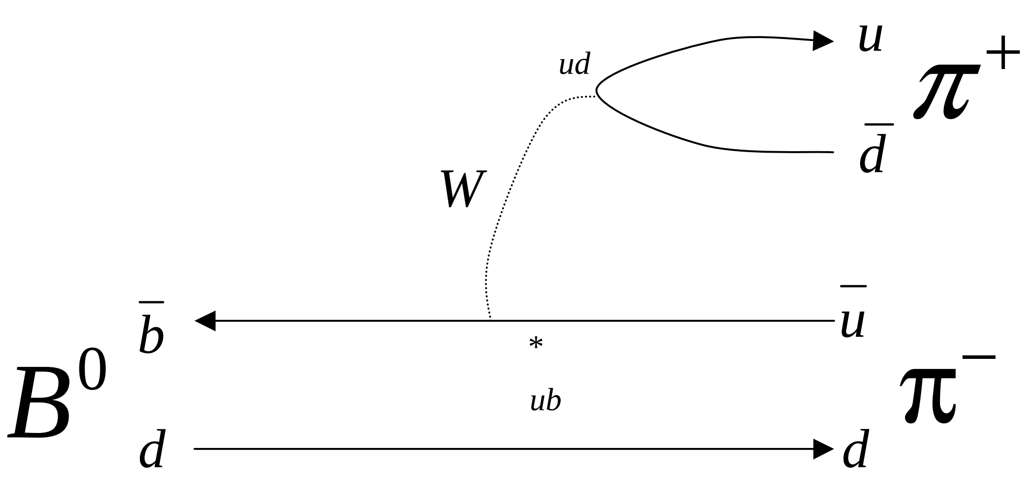
$$\text{probes } \phi_M = \phi_1 \ (= \beta)$$

Predicted Signature



t = Time of tagged decays

“Tin-Plated” Decay



$$\phi_D = \arg(V_{ud}V_{ub}^*) \approx -(\phi_1 + \phi_2)$$

$$\text{probes } \phi_M + \phi_D = \phi_1 - (\phi_2 + \phi_1) = -\phi_2 \quad (= -\alpha)$$

Complicated by “penguin pollution”, but still promising

Review - What B-Factories Do...

- Make LOTS of $b\bar{b}$ pairs at the Υ(4S) resonance in an asymmetric collider.
- Detect the decay of one *B* to a CP eigenstate.
- Tag the flavor of the other *B*.
- Reconstruct the position of the two vertices.
- Measure the *z* separation between them and calculate proper time separation as $t = \Delta z / (\beta_{CM} \gamma_{CM} c)$
- Fit to the functional form

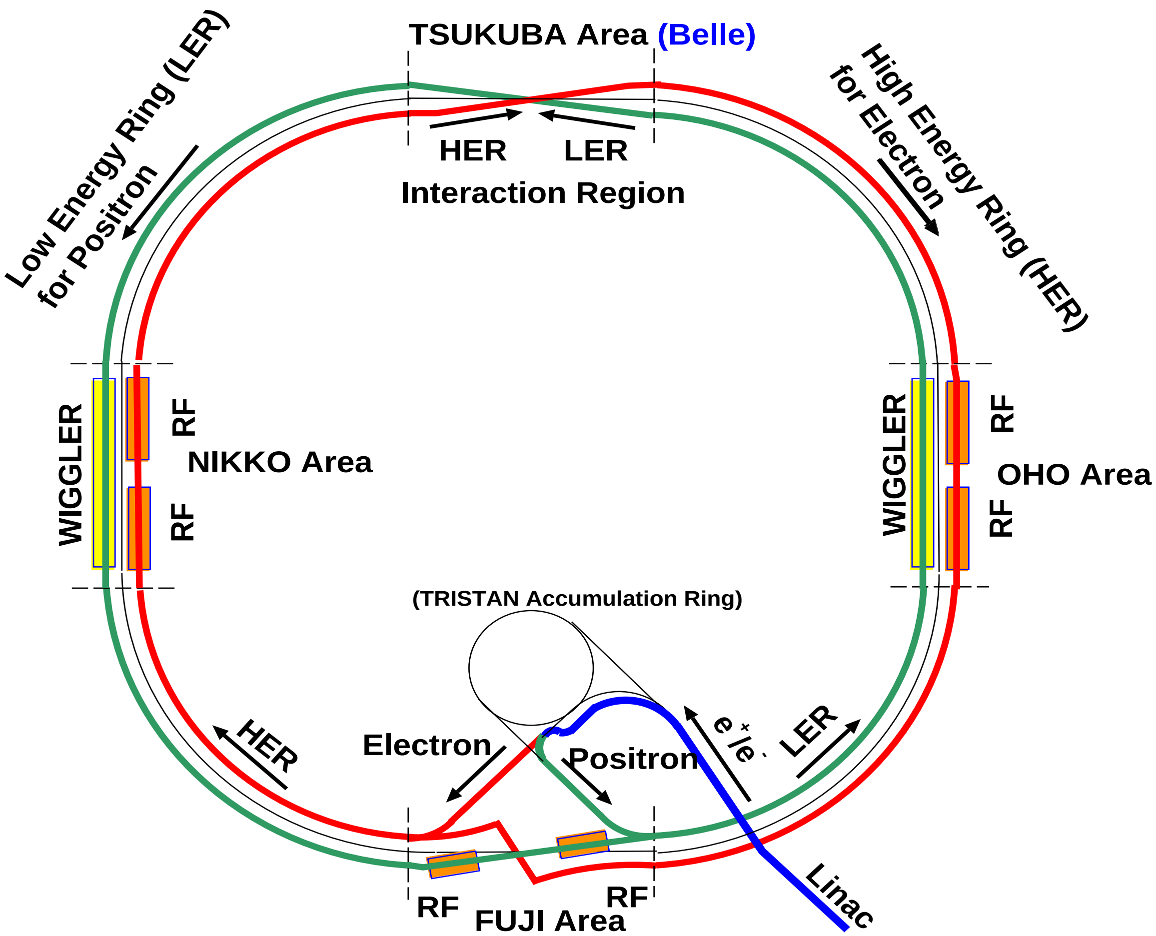
$$e^{-\Gamma|t|}\left[\left\{1 - \eta_{CP} \sin 2\phi_1 \sin \Delta m \Delta t\right\}\right]$$

- Write papers.

Motivations for Accelerator Parameters

- Must be asymmetric to take advantage of Lorentz boost.
- The decays of interest all have branching ratios on the order of 10^{-5} or lower.
  - Need lots and lots of data!
    - Physics projections assume $100\ fb^{-1} = 1yr\ @\ 10^{34}\ cm^{-2}s^{-1}$
    - Would have been pointless if less than $10^{33}\ cm^{-2}s^{-1}$

The KEKB Accelerator



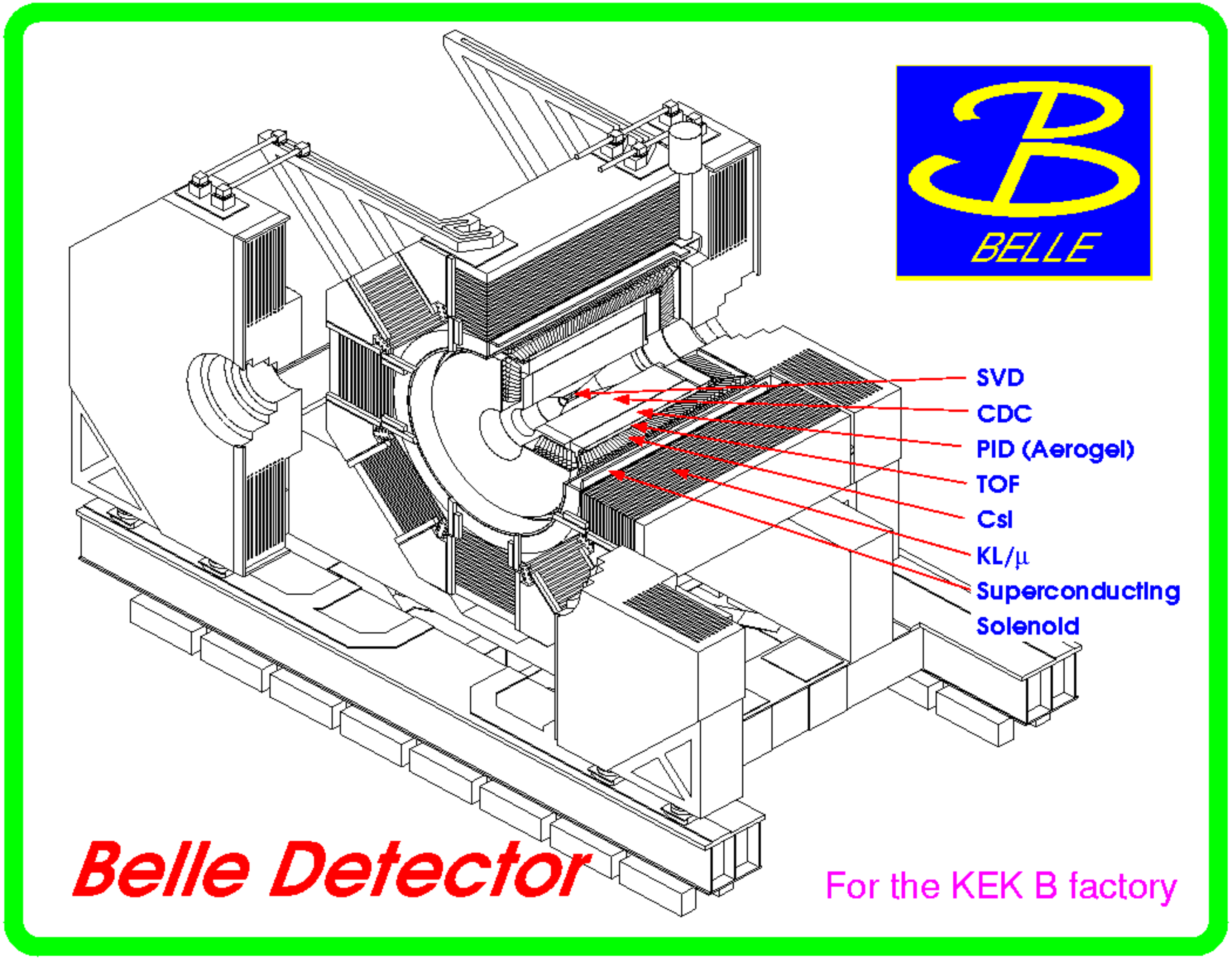
- Asymmetric Rings
  - 8.0GeV(HER)
  - 3.5GeV(LER)
- E_{cm}=10.58GeV= M(ϒ(4S))
- Target Luminosity: $10^{34}s^{-1}cm^{-2}$
- Circumference: 3016m
- Crossing angle: ±11mr
- RF Buckets: 5120
- ⇒ 2ns crossing time

Motivation for Detector Parameters

- Vertex Measurement
  - Need to measure decay vertices to $<100\mu m$ to get proper time distribution.
- Tracking…
  - Would like $\Delta p/p \approx .5\%$ to help distinguish $B \to \pi\pi$ decays from $B \to K\pi$ and $B \to KK$ decays.
  - Provide dE/dx for particle ID.
- EM calorimetry
  - Detect γ's from slow, asymmetric π^0's $\to$ need efficiency down to 20 MeV.
- Hadronic Calorimetry
  - Tag muons.
  - Tag direction of K_L's from decay $B \to \psi K_L$.
- Particle ID
  - Tag strangeness to distinguish B decays from Bbar decays (low p).
  - Tag π's to distinguish $B \to \pi\pi$ decays from $B \to K\pi$ and $B \to KK$ decays (high p).

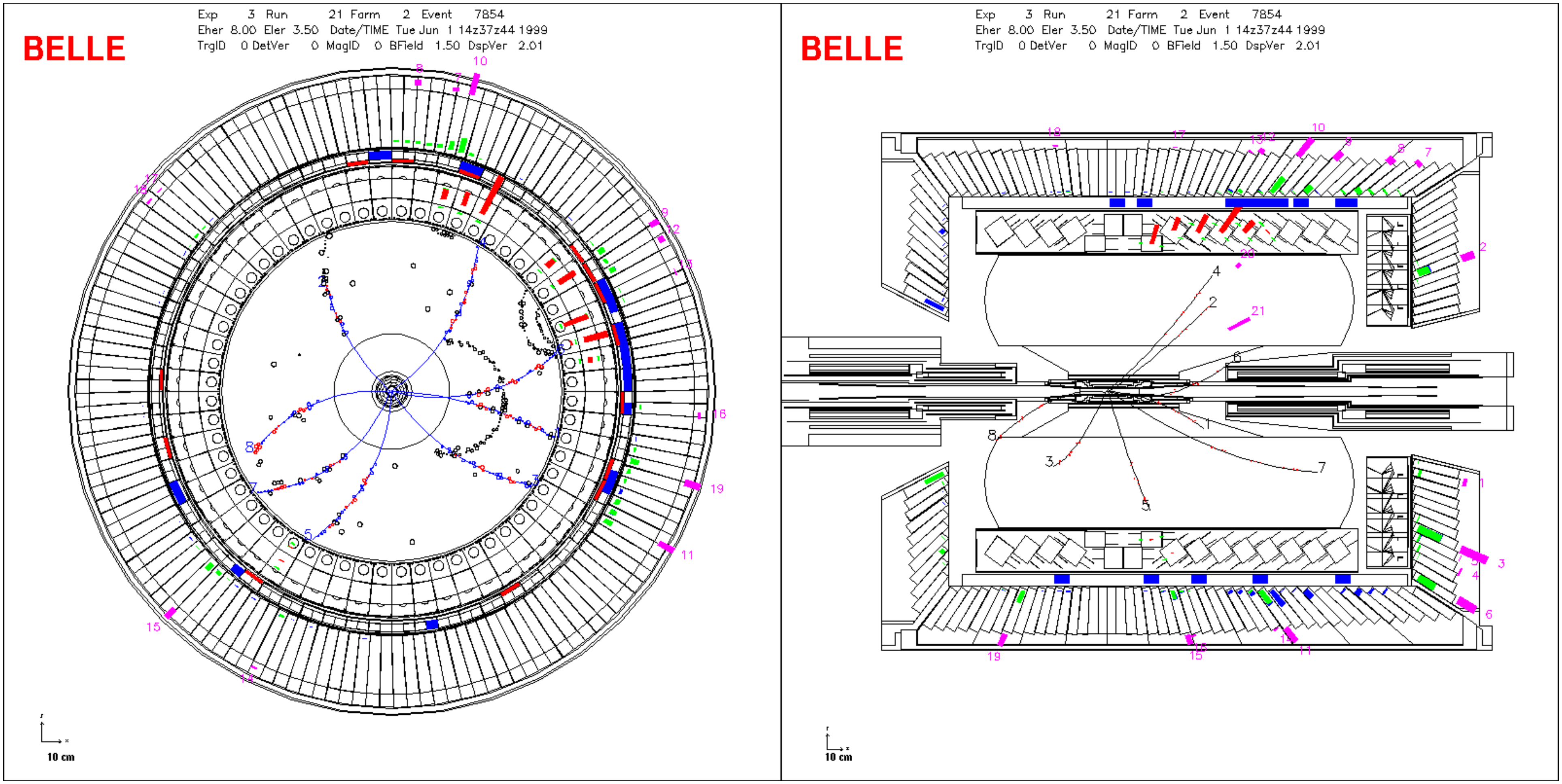
Rely on mature, robust technologies whenever possible!!!

The Detector



All Finished!!

June 1, 1999: Our First Hadronic Event!!



Best Beam Parameters

	LER	HER	
Horizontal Emittance	18 (17)	24 (18)	nm
Beam current	770 (2600)	530 (1100)	mA
Number of bunches	1153 (4600)		
Bunch current	0.67 (.56)	0.46 (.24)	mA
Bunch spacing	2.4 (0.6)		m
Bunch trains	1 (8)		
Horizontal size at IP σ_x^*	103 (140)	123 (140)	µm
Vertical size at IP σ_y^*	2.1 (1.4)	2.1 (1.4)	µm
Emittance ratio $\varepsilon_y/\varepsilon_x$	3.5 (1)	2.6 (1)	%
β_x^*/β_y^*	59 / 0.7	63 / 0.7	cm
beam-beam parameters ξ_x/ξ_y	0.047 / 0.044 (.05/.05)	0.046 / 0.034 (.05/.05)	
Beam lifetime	150 @ 700 mA	300 @ 550 mA	min.

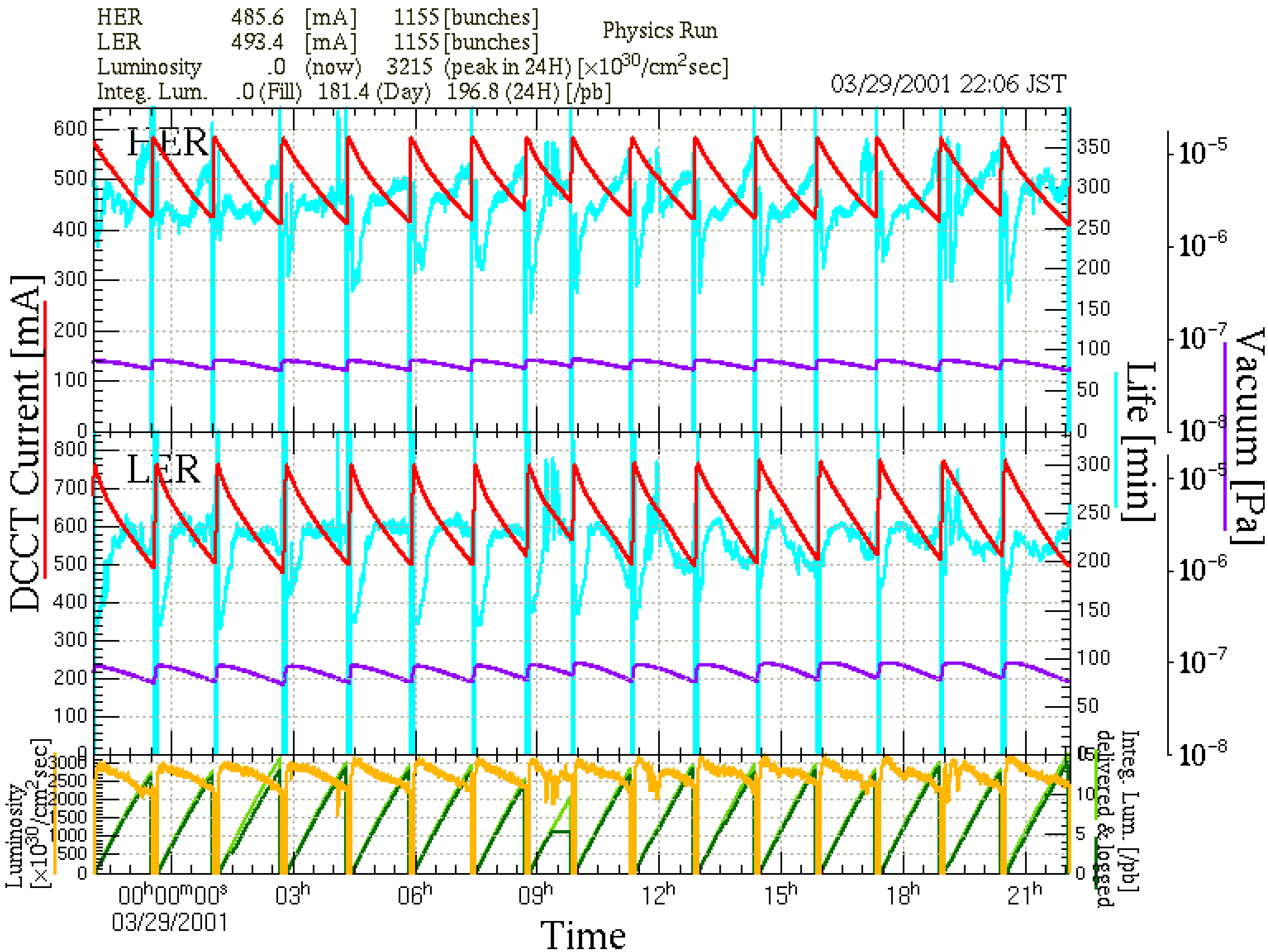
$\Rightarrow 3.41\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

() = design

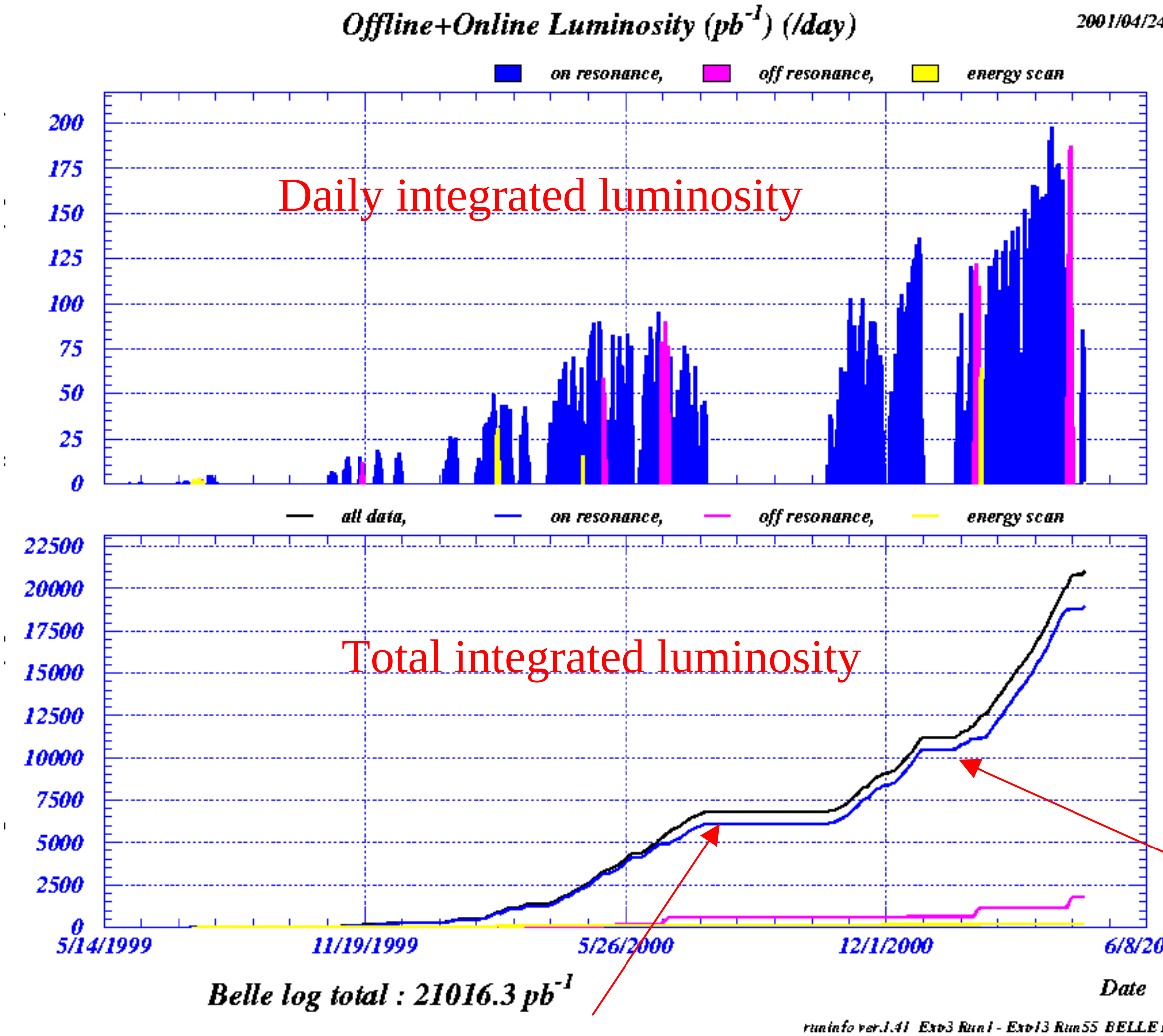
A (not a-)Typical Day

STOP Run
+HV Down
+Fill HER
+Fill LER
+HV Up
+START Run

= 8 Minutes!



Luminosity



Total for first CP Results (Osaka): $\boxed{6.2\ \text{fb}^{-1}}$

Our Records:

World Records!!

- Instantaneous: $3.41\times10^{33}\ \text{cm}^{-2}\text{s}^{-1}$
- Per (0-24h) day: $194.9\ \text{pb}^{-1}$
- Per (24 hr) day: $198.\ \text{pb}^{-1}$
- Per week: $1217.\ \text{pb}^{-1}$
- To date: $\approx 18.5\ \text{fb}^{-1}$ (on peak)

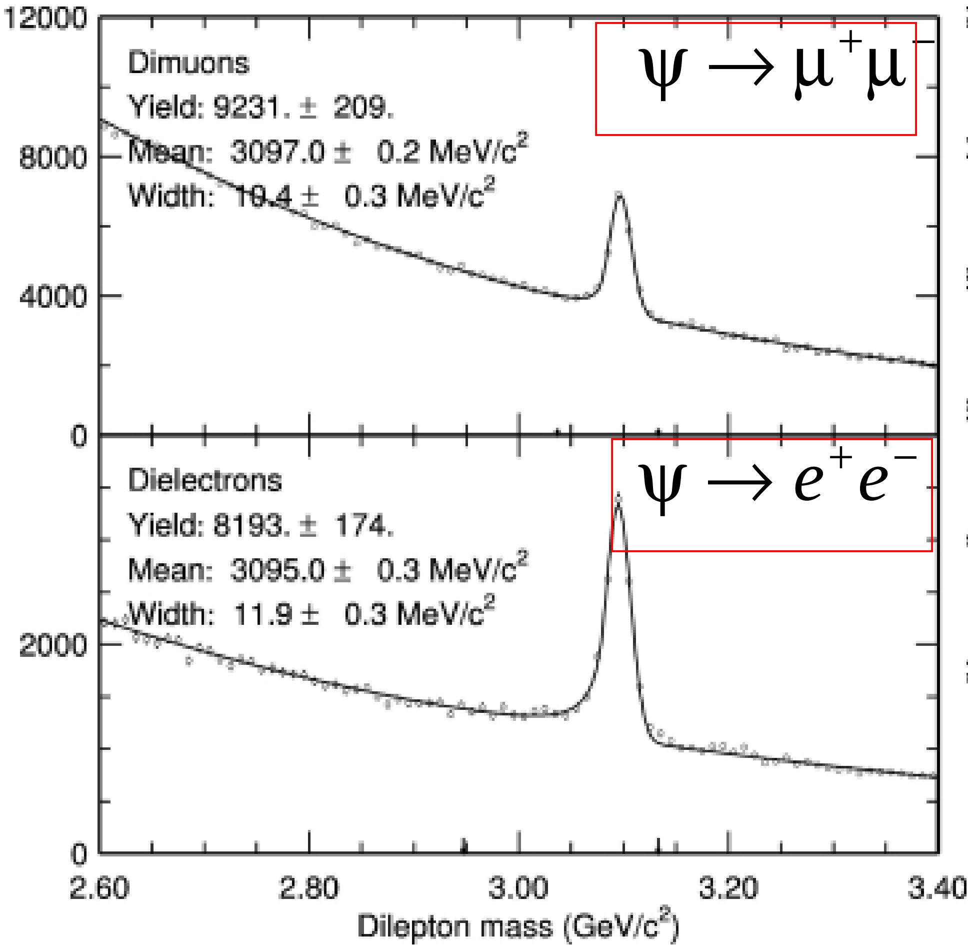
Note: integrated numbers are accumulated!

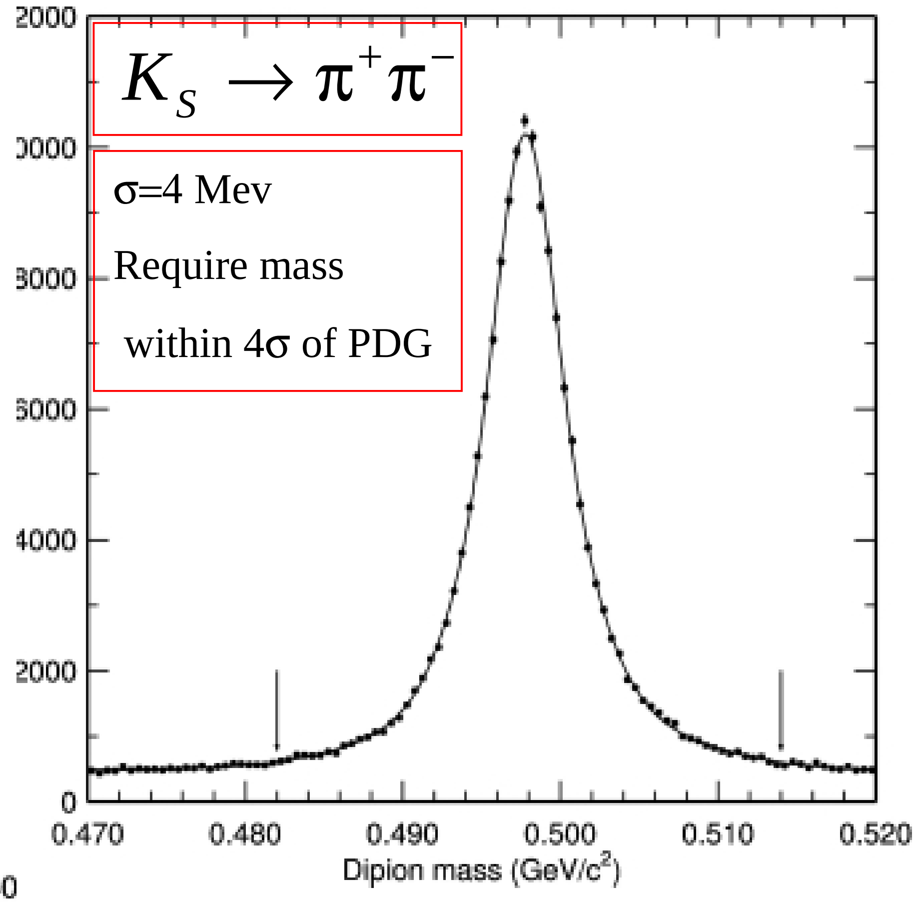
Total for *these* Results: $10.5\ \text{fb}^{-1}$

The Pieces of the Analysis

- Event reconstruction and selection
- Flavor Tagging
- Vertex reconstruction
- CP fitting

J/ψ and K_S Reconstruction





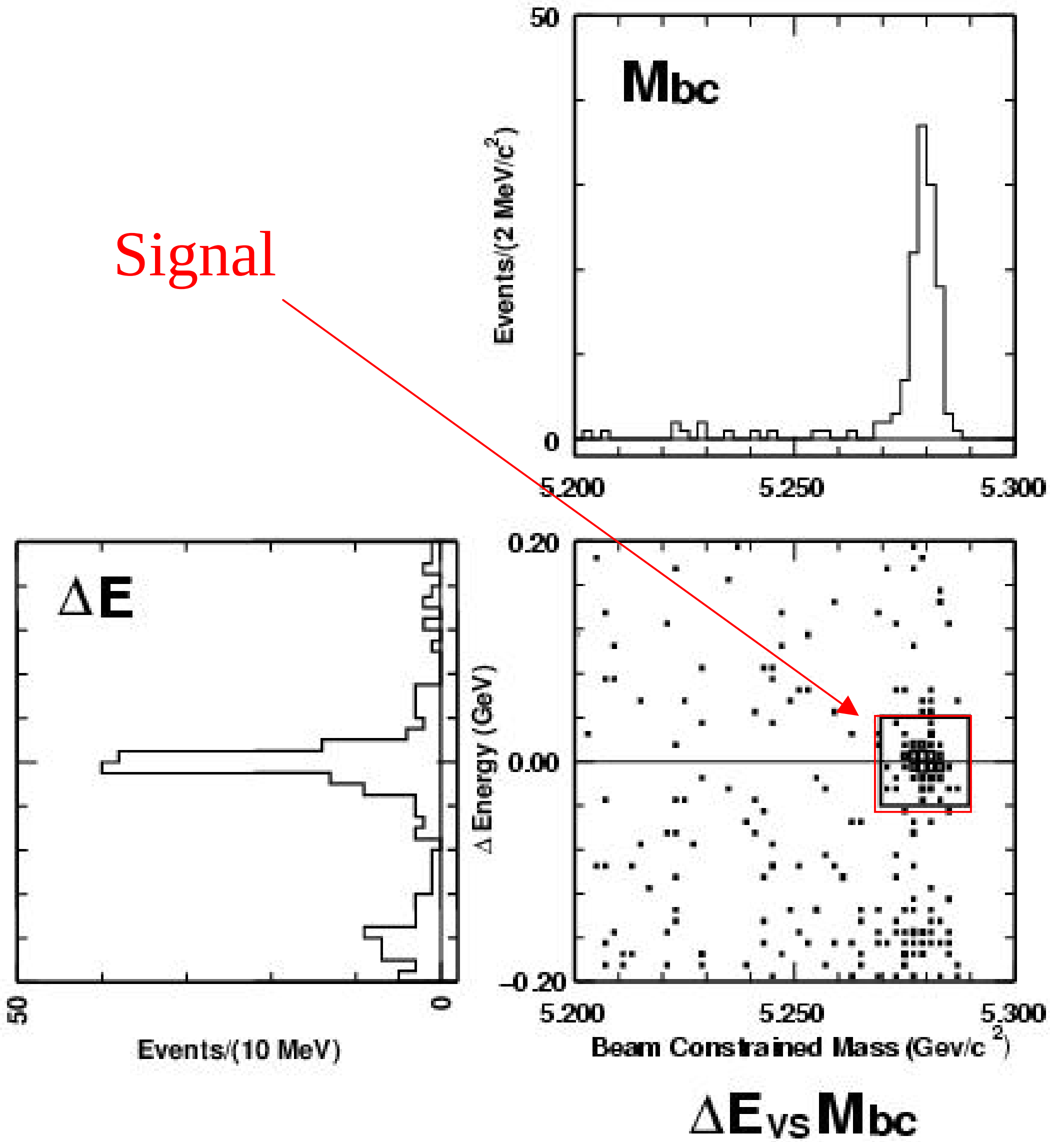
$B \rightarrow \psi K_S$ Reconstruction

- In the CM, both *energy* and *momentum* of a real B^0 are constrained.
- Use "Beam-constrained Mass":

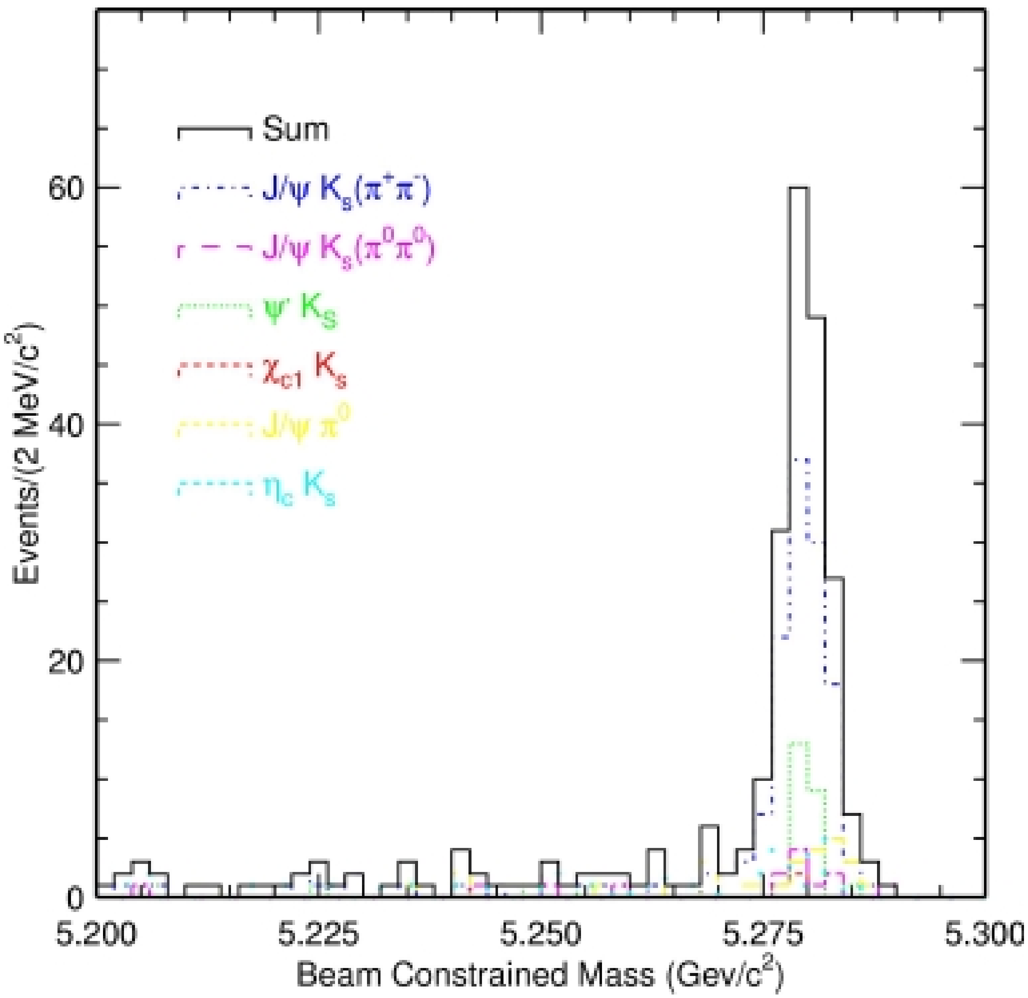
$$M_{BC}^2 = E_{beam}^2 - \left(\sum \vec{p}\right)^2$$

123 Events

3.7 Background

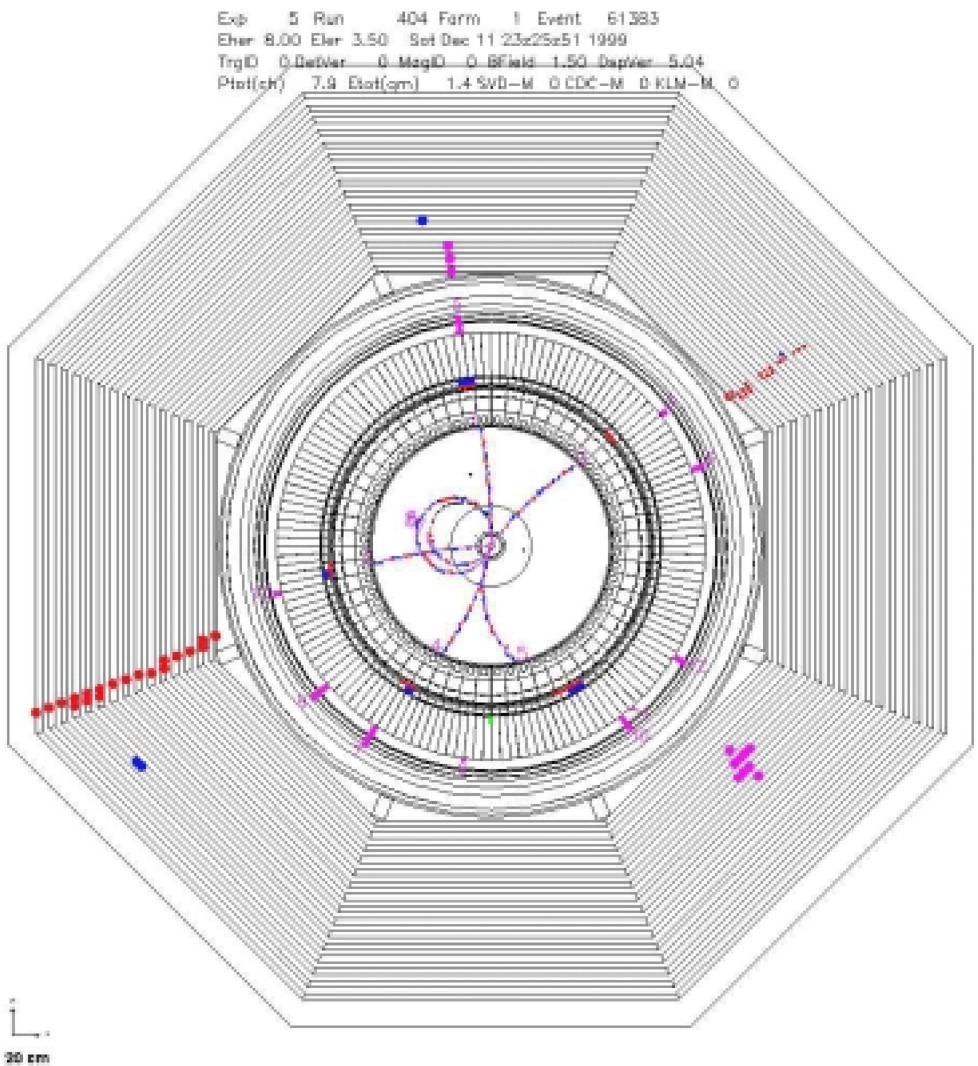


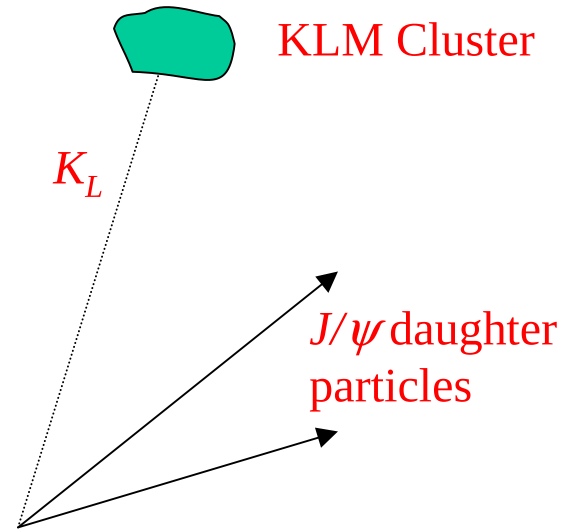
All Fully Reconstructed Modes (i.e. all but ψK_L)



Mode	Events	Background
$B \to \psi K_S$	123.0	3.7
All Others	71.0	7.3
Total	194.0	10.0

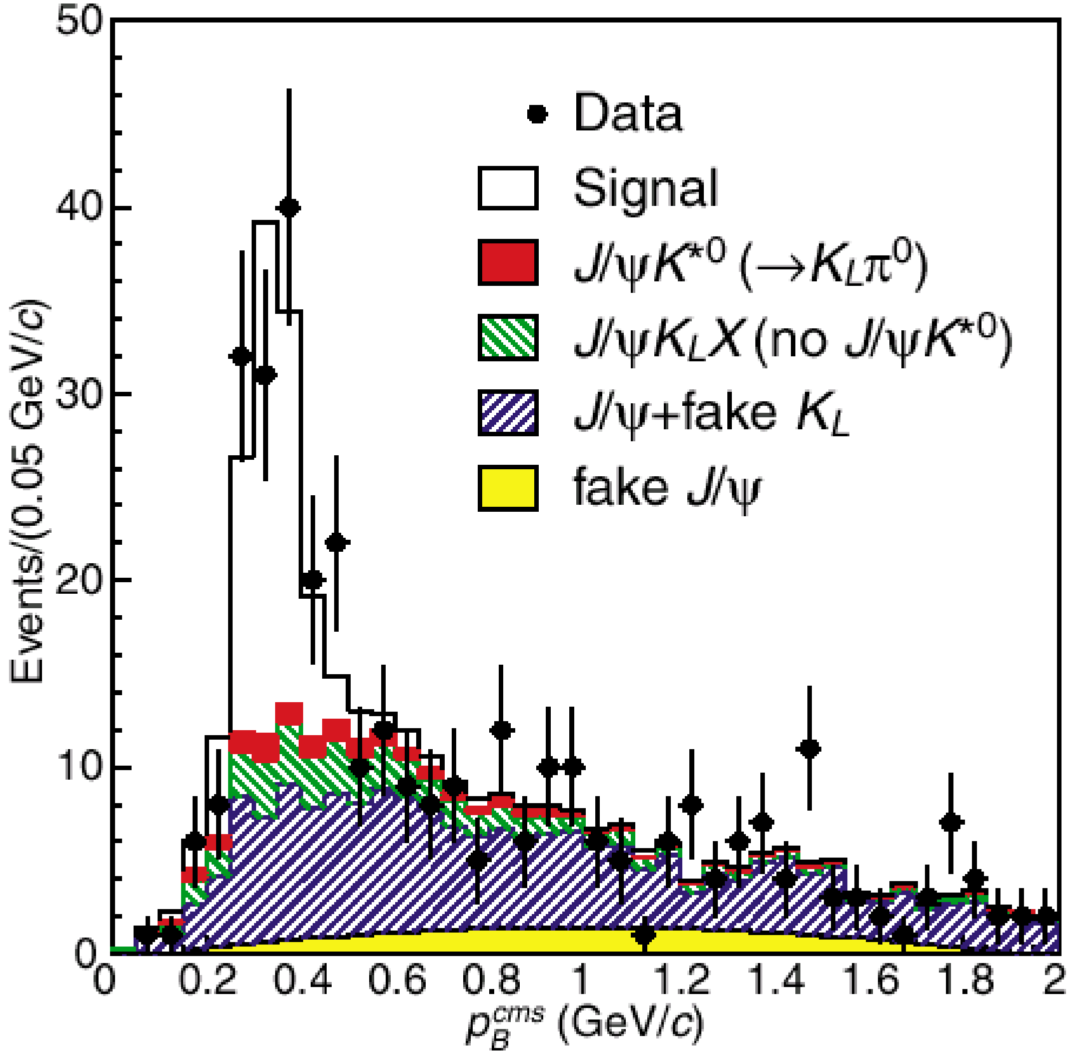
$B \rightarrow \psi K_L$ Reconstruction





- Measure direction (only) of K_L in lab frame
- Scale momentum so that $M(K_L+\psi)=M(B^0)$
- Transform to CM frame and look at $p(B^0)$.

$B \to \psi K_L$ Signal



$0 < p_B^* < 2$ GeV/c

Biases spectrum!

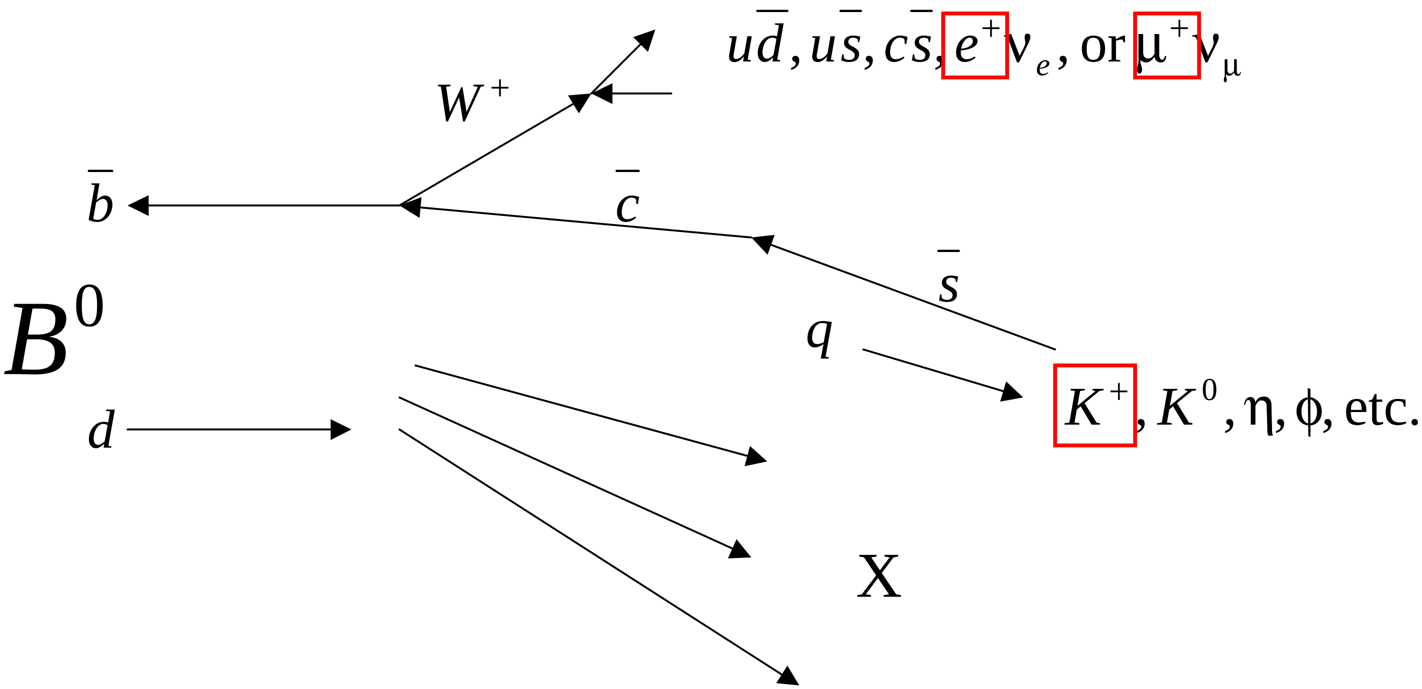
131 Events

54 Background

Complete Charmonium Sample

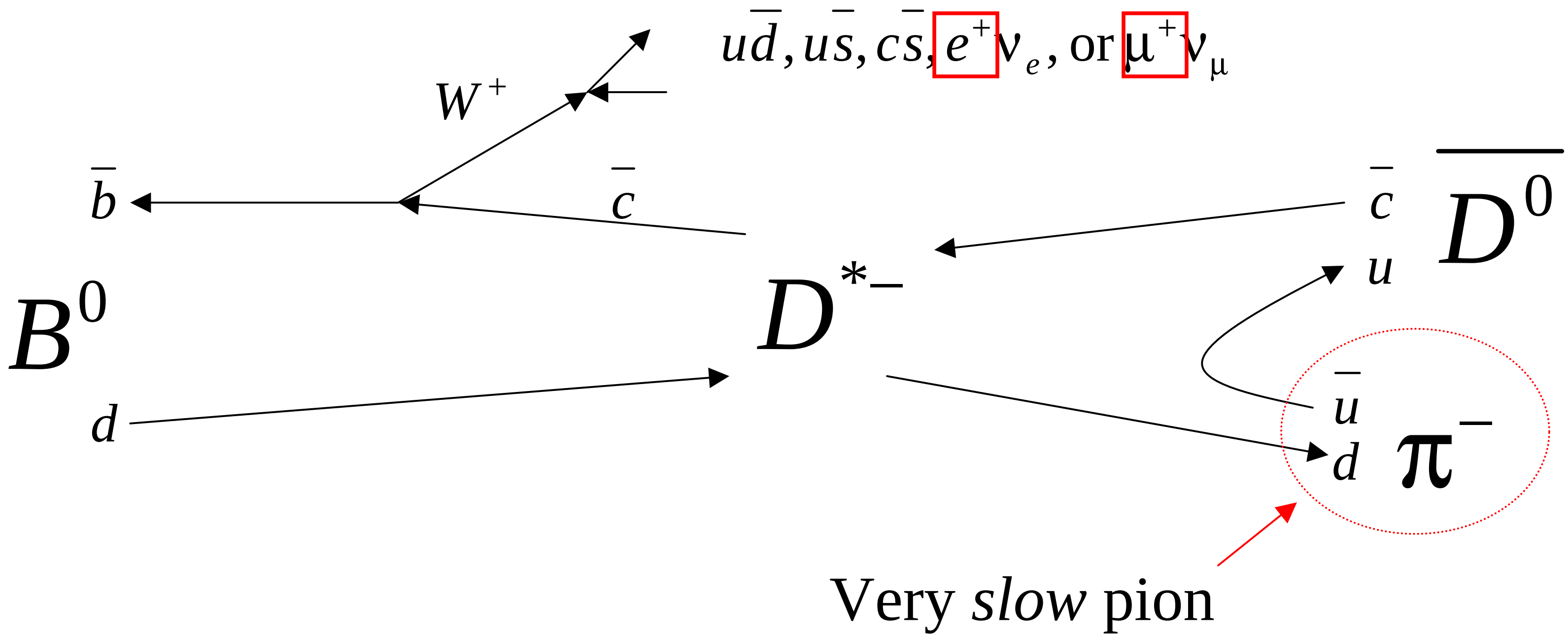
Mode	N_{ev}	N_{bkgd}
$J/\psi(\ell^+\ell^-)K_S(\pi^+\pi^-)$	123	3.7
$J/\psi(\ell^+\ell^-)K_S(\pi^0\pi^0)$	19	2.5
$\psi(2S)(\ell^+\ell^-)K_S(\pi^+\pi^-)$	13	0.3
$\psi(2S)(J/\psi\pi^+\pi^-)K_S(\pi^+\pi^-)$	11	0.3
$\chi_{c1}(\gamma J/\psi)K_S(\pi^+\pi^-)$	3	0.5
$\eta_c(K^+K^-\pi^0)K_S(\pi^+\pi^-)$	10	2.4
$\eta_c(K_SK^+\pi^-)K_S(\pi^+\pi^-)$	5	0.4
$J/\psi(\ell^+\ell^-)\pi^0$	10	0.9
Sub-total	194	11
$J/\psi(\ell^+\ell^-)K_L$	131	54
Total	325	65

Flavor Tagging



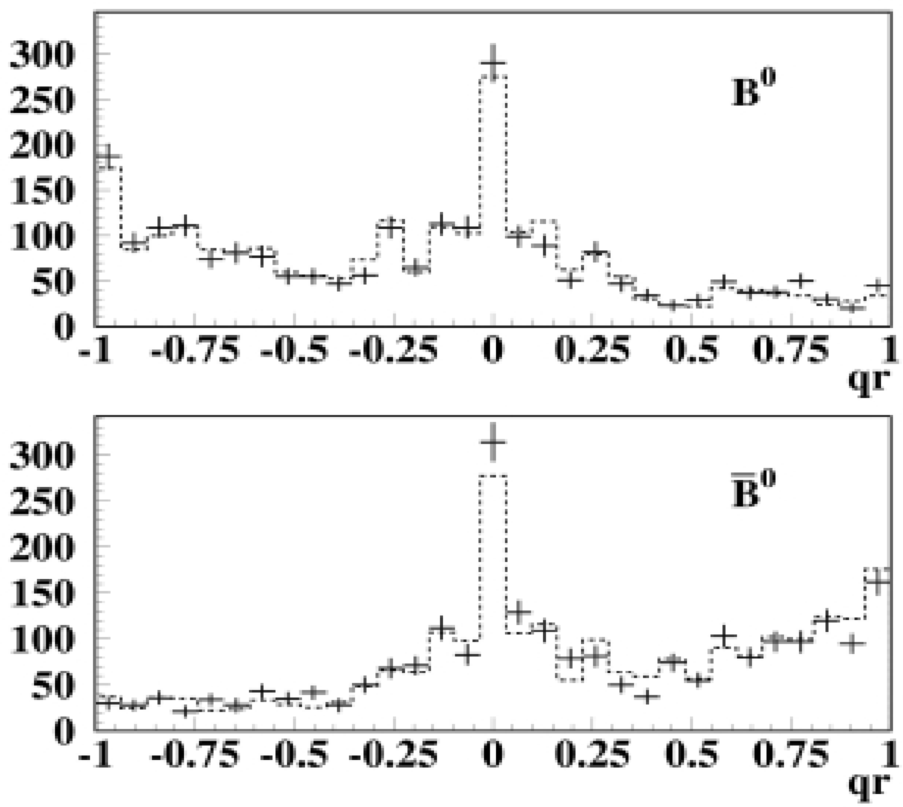
Statistically, B^0's will tend to produce high momentum e^+, μ^+, and/or K^+, while $\overline{B^0}$'s will produce the opposites.

Flavor Tagging (Slow Pion)



B^0's will tend to produce slow π^-.

Comparison Between MC and Data

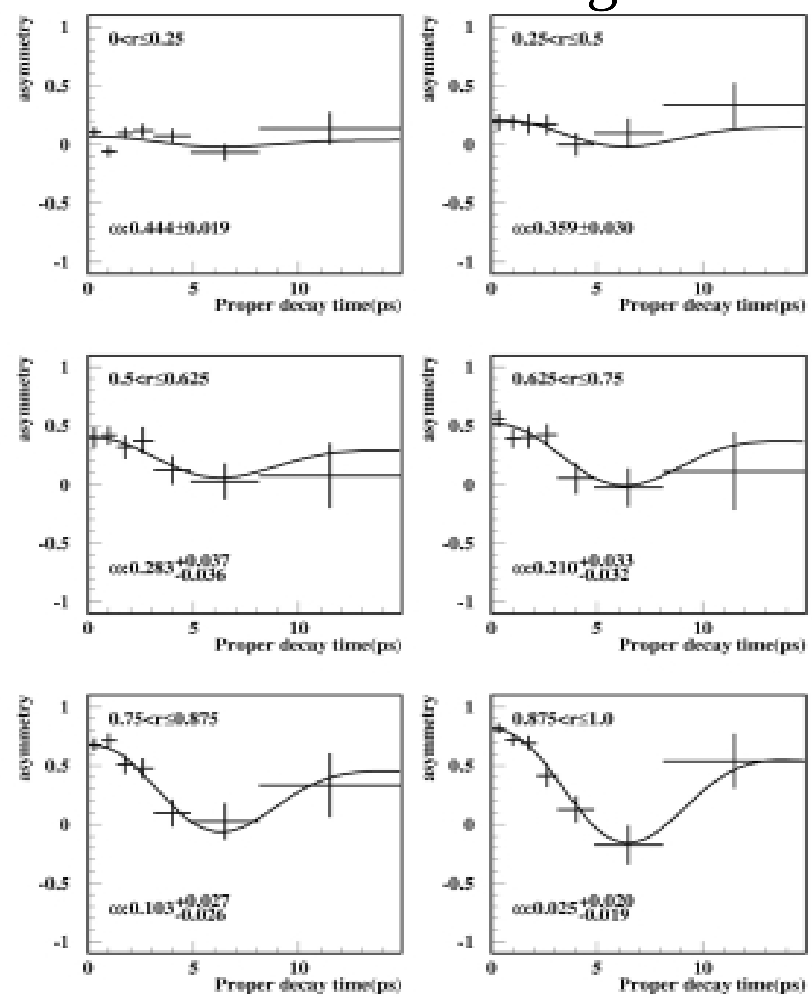


$D^*l\nu$ Events

\+ Data

--- MC

Diluted B-Mixing



Tagging Efficiency

TABLE I. Experimentally determined event fractions (f_l) and incorrect flavor assignment probabilities (w_l) for each r interval.

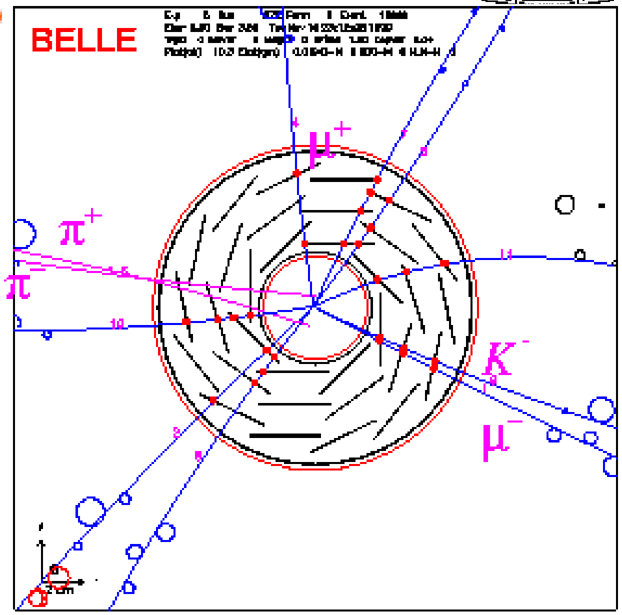
l	r	f_l	w_l
1	0.000 – 0.250	0.393 ± 0.014	$0.470^{+0.031}_{-0.035}$
2	0.250 – 0.500	0.154 ± 0.007	$0.336^{+0.039}_{-0.042}$
3	0.500 – 0.625	0.092 ± 0.005	$0.286^{+0.037}_{-0.035}$
4	0.625 – 0.750	0.100 ± 0.005	$0.210^{+0.033}_{-0.031}$
5	0.750 – 0.875	0.121 ± 0.006	$0.098^{+0.028}_{-0.026}$
6	0.875 – 1.000	0.134 ± 0.006	$0.020^{+0.023}_{-0.019}$

Experimentally determined w values in each *r* region

Tagging efficiency ε_T = 99.4% (vs. 99.3% in MC)

Effective efficiency $\varepsilon_{eff} = \varepsilon_T(1-2w)^2$ = **27.0%** (vs. 27.4% in MC)

Vertex Reconstruction



- Common requirements in vertexing
  - # of associated SVD hits > 2 for each track
  - IP constraint in vertex reconstruction
- *CP* side vertex reconstruction
  - Event is rejected if reduced $\chi^2 > 100$.
- Tag side vertex reconstruction
  - Track parameters measured from *CP* vertex must satisfy:
    - $|\Delta z|<1.8$mm, $|\sigma z|<500\mu$m, $|\Delta r|<500\mu$m
  - Iteration until reduced $\chi^2 < 20$ while discarding worst track.
- $|z_{CP} - z_{\mathrm{tag}}|<2$mm $(\approx 10\,\tau_B)$

Overall efficiency = ~87%. In total 282 events for the CP fit.

CP Fit (Probability Density Function)

$$f(\Delta t; \sin 2\phi_1) = \mathrm{e}^{-\frac{|\Delta t|}{\tau_B}} \left(1 \pm \sin 2\phi_1 \sin x_d \frac{\Delta t}{\tau_B} \right)$$

$$PDF = \int (1 - f_{BG}) f(t') R(t' - \Delta t)\, \mathrm{d}t' + f_{BG} PDF_{BG}(\Delta t)$$

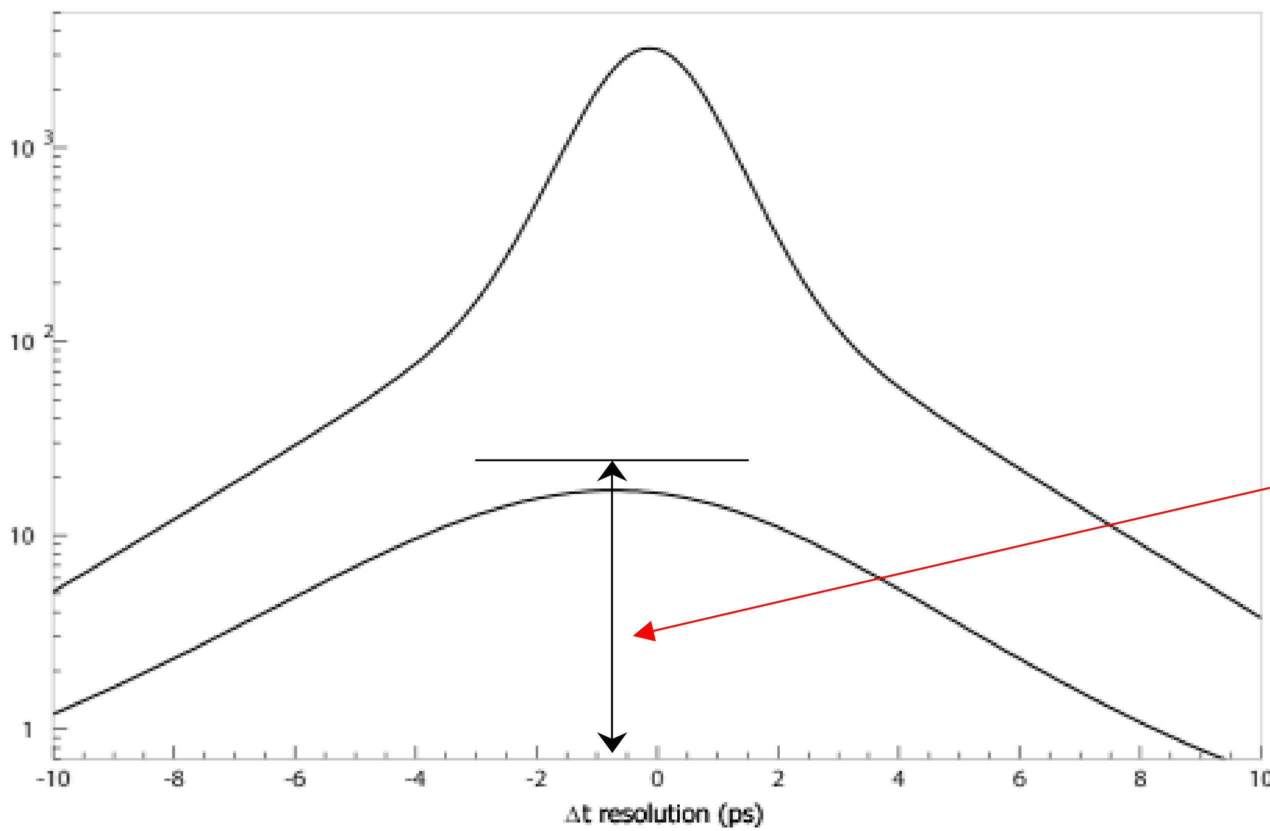
•f_{BG} = background fraction. Determined from a 2D fit of *E* vs *M*.

•$R(\Delta t)$ = resolution function. Determined from D^*'s and MC.

•$PDF_{BG}(\Delta t)$ = probability density function of background. Determined from ψK sideband (210 events).

Resolution Function

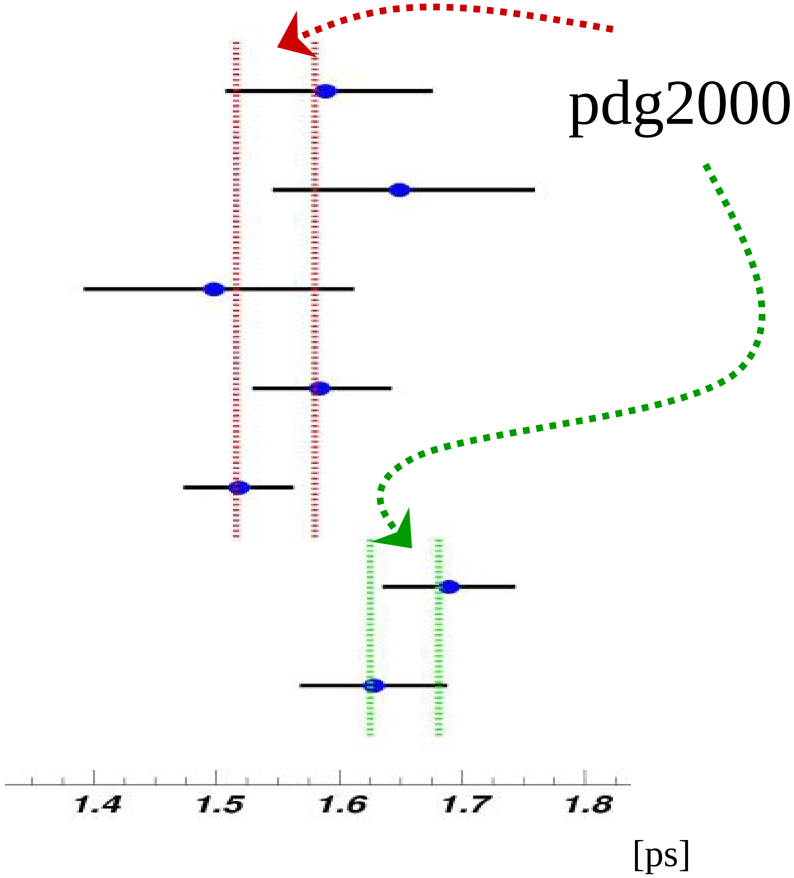
Fit with a double-Gaussian…



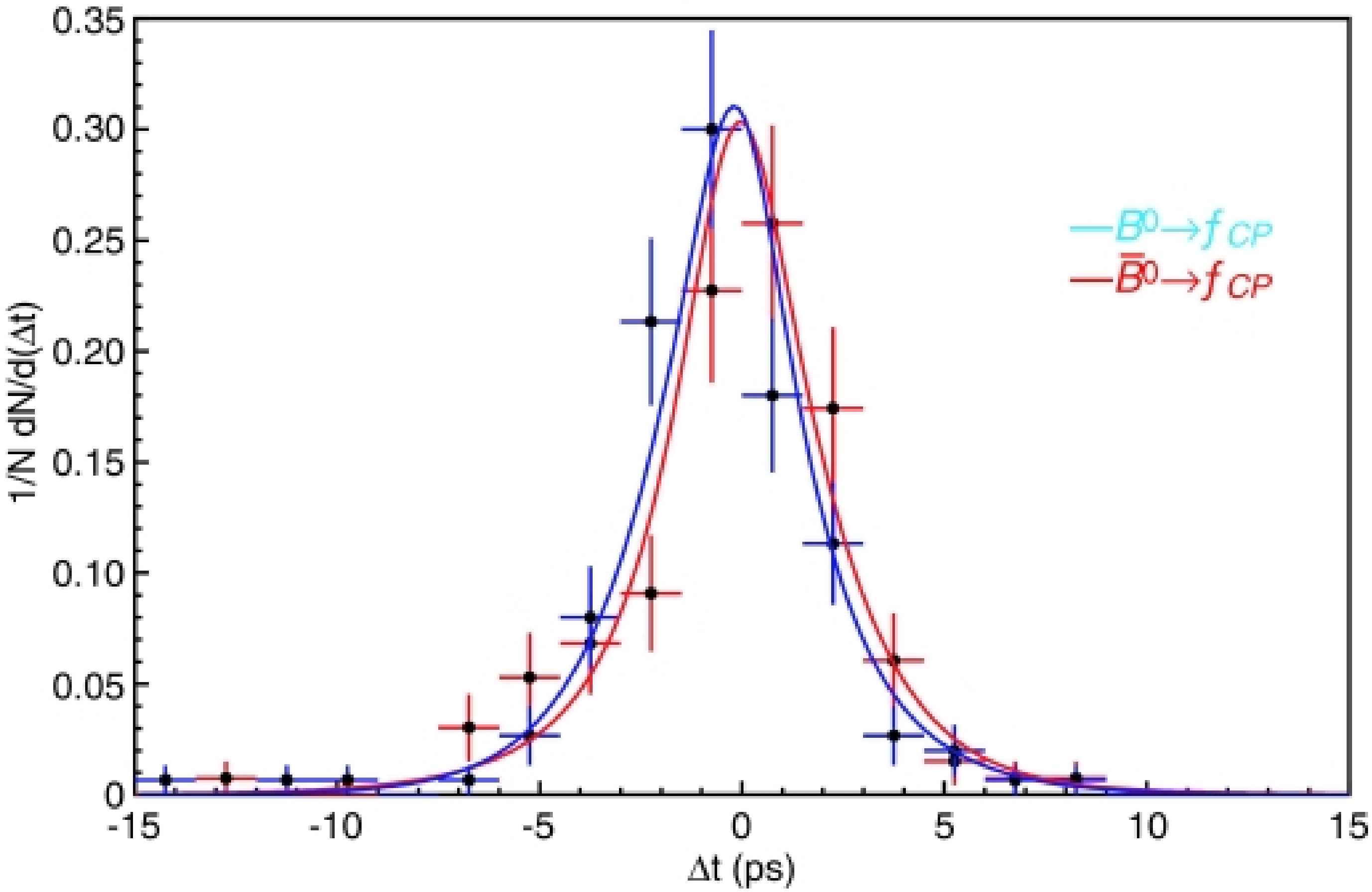
μ_{main}	-0.09 ps
σ_{main}	1.54 ps
μ_{tail}	-0.78 ps
σ_{tail}	3.78 ps
f_{tail}	0.018

Test of Vertexing – B Lifetime

Mode	Lifetime (ps)
$B^0 \to D^+\pi^-$	$1.59^{+.09}_{-.08}$
$D^{*+}\pi^-$	$1.65^{+.11}_{-.10}$
$D^{*+}\rho^-$	1.50 ± 0.11
Combined	1.59 ± 0.05
$D^{*+}l^-\nu$	1.52 ± 0.05
$B^- \to D^0\pi^-$	1.68 ± 0.05
$D^{*0}l^-\nu$	1.63 ± 0.06



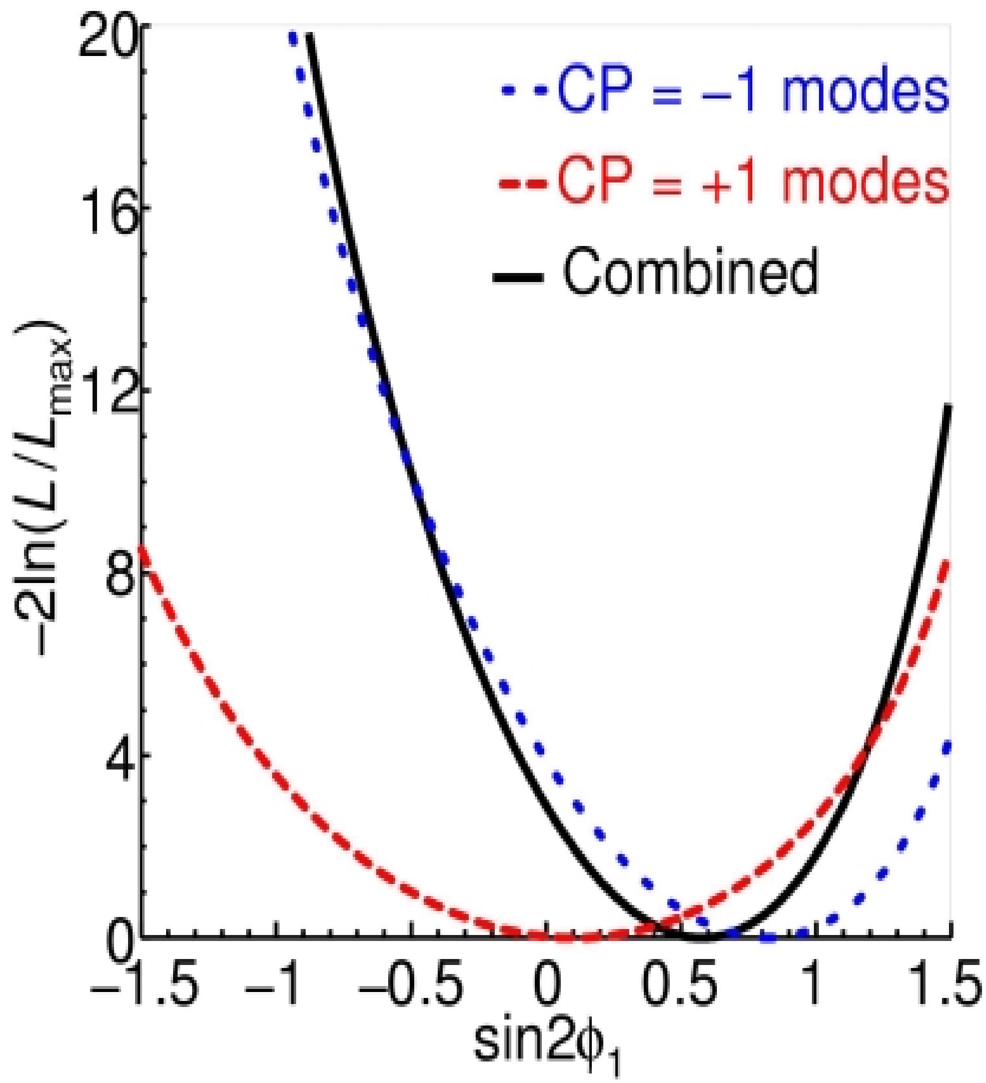
The Combined Fit (All Charmonium States)



$$\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)$$

Individual Subsamples

Mode	Fit (stat. err.)
Non-CP	0.065 ± 0.075
$B \to \psi K_S$	$1.21^{+.40}_{-.47}$
$B \to \psi K_L$	-0.04 ± 0.60
CP = -1	$0.82^{+.36}_{-.41}$
CP = +1	$0.10^{+.57}_{-.60}$
All CP	$0.58^{+.32}_{-.34}$



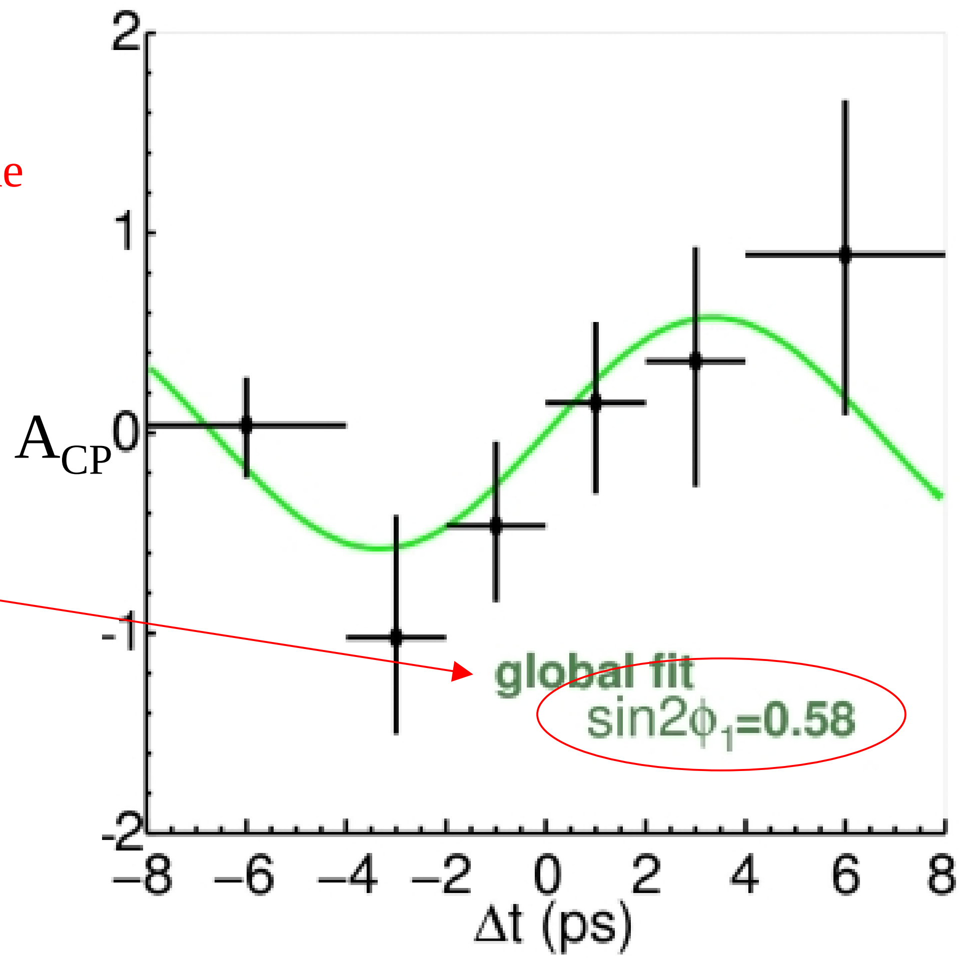
Consistency Check

Plot asymmetry in individual time bins…

Fix at PDG value

$$\sin 2\phi_1 \sin \Delta m \Delta t$$

Our fit



Sources of Systematic Error

Source	σ_+	σ_-
Wrong tag fraction	+.05	-.07
Resolution for signal	+.01	-.01
Background Shape	+.01	-.01
Physics Parameters	+.03	-.04
IP Profile	+.02	-.01
Background (not K_L)	+.03	-.02
Background (K_L)	+.05	-.05
Total	**+.09**	**-.10**

- Bottom Line

$$\boxed{\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)^{+.09}_{-.10}(syst.)}$$

Published in **Phys.Rev.Lett. 86, 2509 (2001)**

Other Recent Publications

- "Measurement of B^0_d - B^0_d-bar Mixing Rate from the Time Evolution of Dilepton Events at Upsilon(4S)" **PRL 86,3228**
- "Observation of Cabibbo suppressed B -> D(*)K- decays at Belle"
  (*submitted to PRL* **)**
- "A Measurement of the Branching Fraction for the Inclusive B->Xs gamma Decays with Belle" (*submitted to PLB)*
- "Measurement of Inclusive Production of Neutral Pions from Upsilon(4S) Decays" (*submitted to PRL)*

+ Several More in the Pipeline!!

Summary and Outlook

- Belle is working very well!!
- Our current value of *sin2ϕ_1*, based on 10.5 fb^{-1} of data is

$$\boxed{\sin 2\phi_1 = .58^{+.32}_{-.34}(stat)^{+.09}_{-.10}(syst.)}$$

- This is consistent with the BaBar value of

$$\sin 2\beta = .34 \pm .20(stat) \pm .05(syst.)$$

and with other previous results (CDF, LEP)

- The probability of observing this value if CP is conserved is 4.9%
- The next few years should be very exciting!

Key Belle Milestones

- Early 1990's: Japanese groups begin working.
- January 1994: Collaboration forms.
- April 1995: TDR Submitted.
- …lots of work by lots of people in lots of places...
- Dec 18, 1998: Belle detector completed (including SVD)
- Jan 26, 1999: First cosmic ray with full detector.
- May 1, 1999: Belle rolled into place.
- June 1, 1999: First hadronic event!!!!!
- November 9, 1999: Integrated luminosity exceeds 100 pb^{-1}
- February 29, 2000: Integrated luminosity exceeds 1 fb^{-1}
- July 28, 2000: First CP results presented at Osaka (used 6.2 fb^{-1})

What about ϕ_3?

- Corresponding decay would be $B_s \rightarrow \rho\ K_{S,}$, but…
  - Require move to $\Upsilon(5s)$ resonance (messier)
  - Time dependent B_s mixing not possible.
- $\Rightarrow$ Have to find another way.

Are Two B-Factories Too Many?

- These are not discovery machines!
- Any interesting physics would manifest itself as small deviations from SM predictions.
- People would be very skeptical about such claims without independent confirmation.
- Therefore, the answer is NO (two is not *one* too many, anyway).

Differences Between PEP-II (BaBar) and KEKB (Belle)

- PEP-II has complex IR optics to force beams to collide head-on.
  - Pros: Interaction of head-on beams well understood.
  - Cons: Complicates IR design.
    More synchrotron radiation.
    Can't populate every RF bucket.

- In KEK-B, the beams cross at ± 11 mr.
  - Pros: Simple IR design.
    Can populate every RF bucket.
    Lower (but not zero!!!) synchrotron radiation.
  - Cons: Crossing can potentially couple longitudinal and transverse instabilities.

At present, both designs seem to be working.

Differences (cont'd)

Readout:

• BaBar uses an SLD-inspired system, based on a continuous digitization. The entire detector is pipelined into a software-based trigger.

Pros: Extremely versatile trigger.
Less worry about hardware-based trigger systematics.
Can go to very high luminosities.

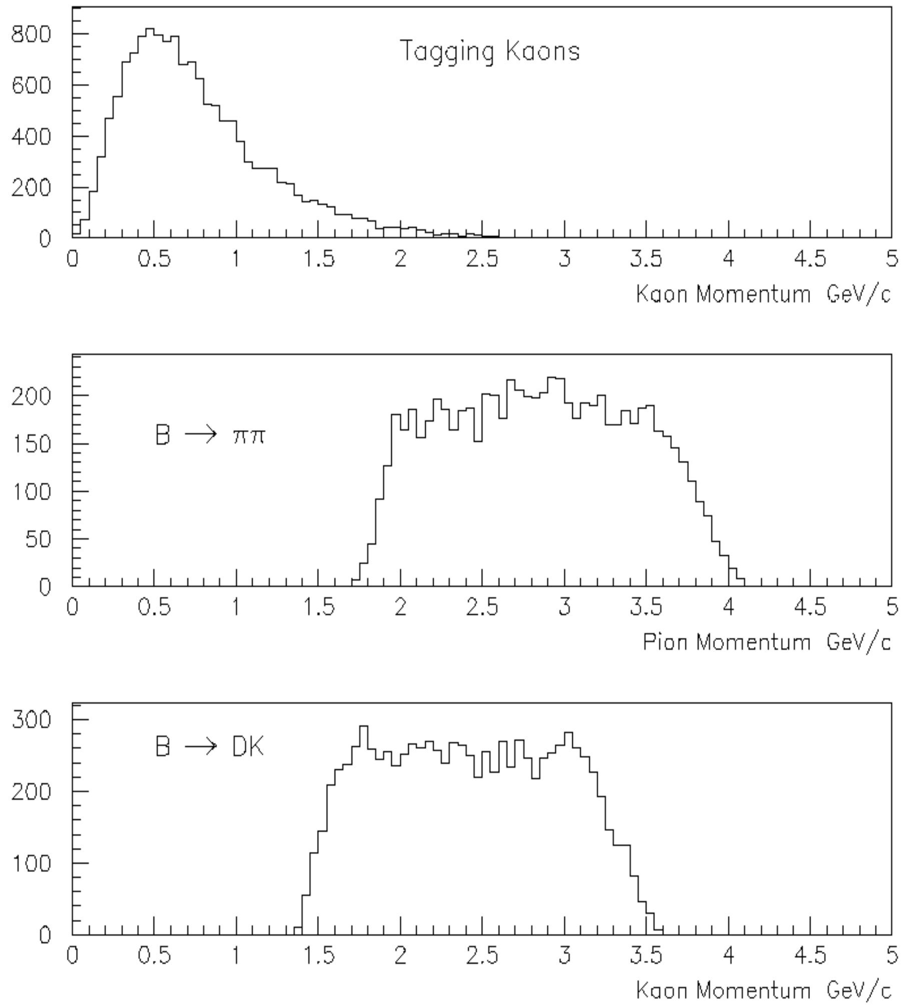
Cons: Required development of lots of custom hardware.

• Belle's readout is based on converting signals to time-pulses. The trigger is an "old-fashioned" hardware-based level one. Events satisfying level one are read out after a 2 μs latency.

Pros: Simple.
Readout relies largely on "off-the-shelf" electronics.

Cons: Potential for hardware-based trigger systematics.
Possible problems with high luminosity.

Particle ID needs

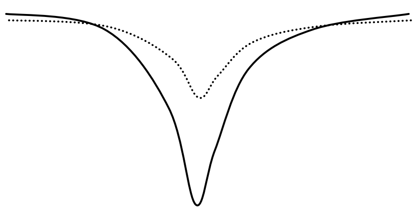


Technology	Pros	Cons	Comment
TOF	Simple.	Only for low momentum.	Included in Belle
dE/dx	Proven. Comes for free.	Only for low momentum	Included in Belle.
TMAE based RICH	Proven in SLD and DELPHI	Universally despised.	Rejected.
CSI RICH	Once seemed promising.	No one could build a working prototype.	Rejected.
DIRC	Rugged. Excellent separation.	New. Contstrants on detector geometry	Babar choice
Aerogel threshold Cerenkov	Simple.	Barely adequate	Belle choice

Nuts and Bolts: Readout

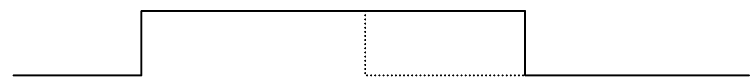
Philosophy: Signal ⇒ Time Pulse ⇒ TDC (LeCroy 1877) ⇒ Generic DAQ

Analog Signal

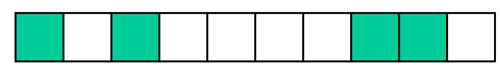


⇒

Variable *Length* Pulse



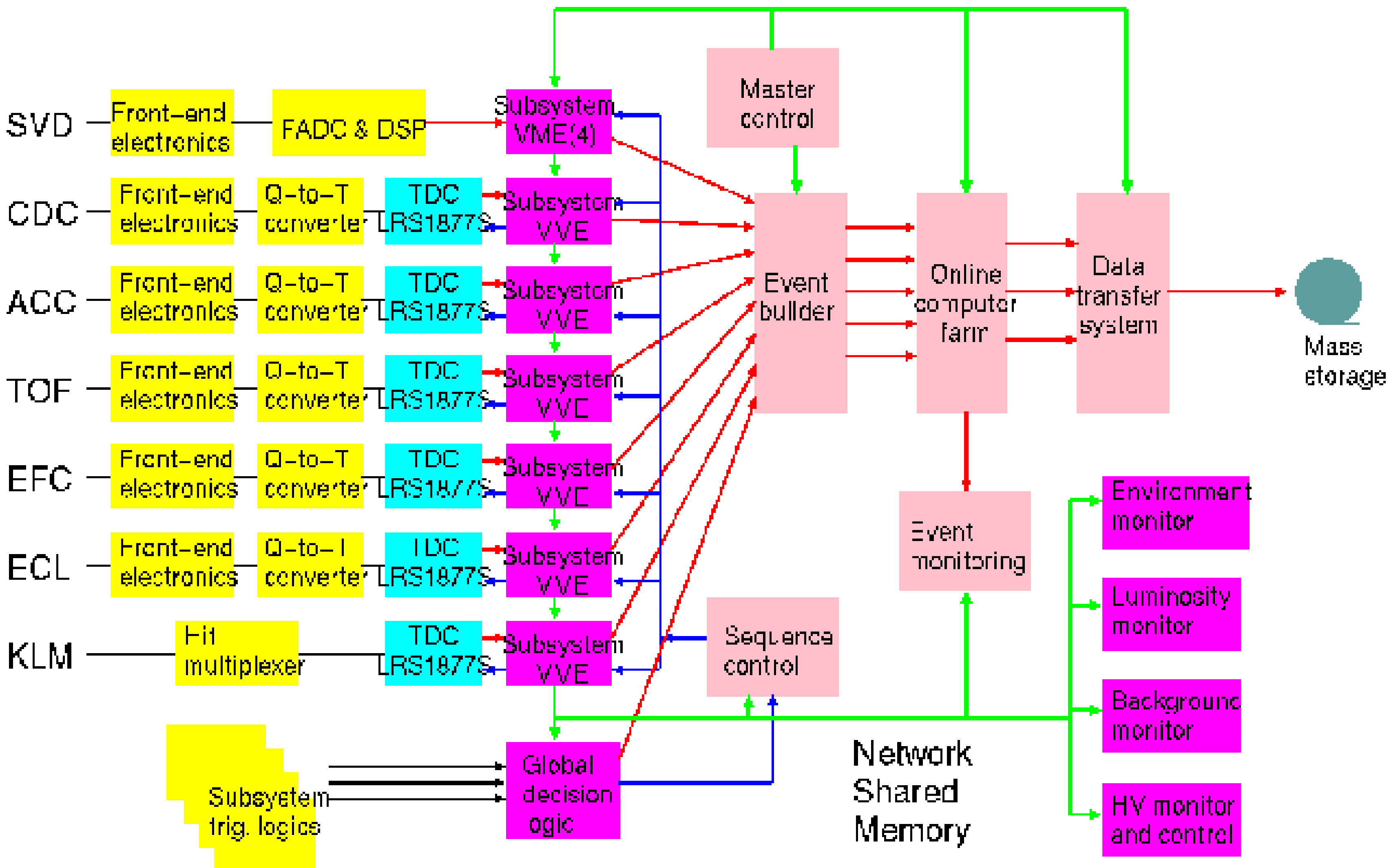
Binary Data



⇓

Pulse Train Encoding (Hit ⇒ Edge)

DAQ Overview



Nuts and Bolts: Analysis Framework

- Belle AnalysiS Framework (Pronounced “BASF”):
  - Developed entirely with freeware (GNU, Cernlib, CLHEP, etc)
  - Script Driven
  - Based on individual data generation/processing modules (C++ classes), with common members (hist_def, begin_run, event, etc).
  - All data (raw, intermediate, physics, constants) arranged in named banks based on the PANTHER bank system and stored in files.
  - Individual banks or groups of banks can be read or written to files at any point in data processing.
  - Constants stored in database based on Postgresql.
  - Multiprocessing supported for read/write file access and histogram/ntuple generation.

Example BASF full MC Job

Specify Processing Modules

```
path add_module main qq98 gsim acc_mc
path add_module main calcdc calsvd reccdc recsvd trasan trak
path add_module main AnadEdx ext rectof rececl_cf
path add_module rececl_match rececl_gamma
path add_module main rececl_pi0 rec_acc mu2 klid
path add_module v0finder rec2mdst evtcls sakura
path add_module main kid_mc_mon AnadEdx_mc_mon tof_mc_mon
path add_module main table_list
```

Number of Processors

```
nprocess set 5
```

Pass Parameters to Modules

```
module put_parameter qq98 USER_TABLE\b02psikl.dec
```

Histogram File

```
histogram define signal_tag.hbk
initialize
```

Specify Tables to Save

```
table savebr belle_begin_run
table save belle_event
table save mdst_all
table save evtcls_all
table save gsim_rand
table save hepevt_all
```

Output File

```
output open signal.evt
```

Go!

```
generate_event 10000
terminate
```

Example BASF Analysis Job

Will look for user_ana.so	`path add_module main user_ana`
	`histogram define user.hbk`
	`initialize`
Could be real data or MC	`process_event signal.evt`
	`terminate`

Example User Analysis (user_ana.cc)

Access charged track PANTHER bank

Loop over list of individual objects (tracks)

Manipulate using standard tools

```
// Charged tracks
Mdst_charged_Manager &ChgMgr = Mdst_charged_Manager::get_manager();
for(vector<Mdst_charged>::iterator it = ChgMgr.begin();
          it != ChgMgr.end() ; it++) {
    // Form a 4-vector for this particle
    Vector3 p_i(it->px(),it->py(),it->pz());
    Vector4 p4_i(p_i,sqrt(p_i.mag2()+EMass2));
    // Now loop over the second particle
    for(vector<Mdst_charged>::iterator jt = it+1;
          jt != ChgMgr.end() ; jt++) {
      // Require opposite charges
      if((jt->charge())==(it->charge())) continue;
         // If we're here, we have two tracks of opposite charge.
         // Calculate the pair mass
         Vector3 p_j(jt->px(),jt->py(),jt->pz());
         Vector4 p4_j(p_j,sqrt(p_j.mag2()+EMass2));
         Vector4 p4 = p4_i+p4_j;
         float pairMass = p4.mag();  // Calculate the pair mass
    }
}
```

Event by Event Tagging Quality

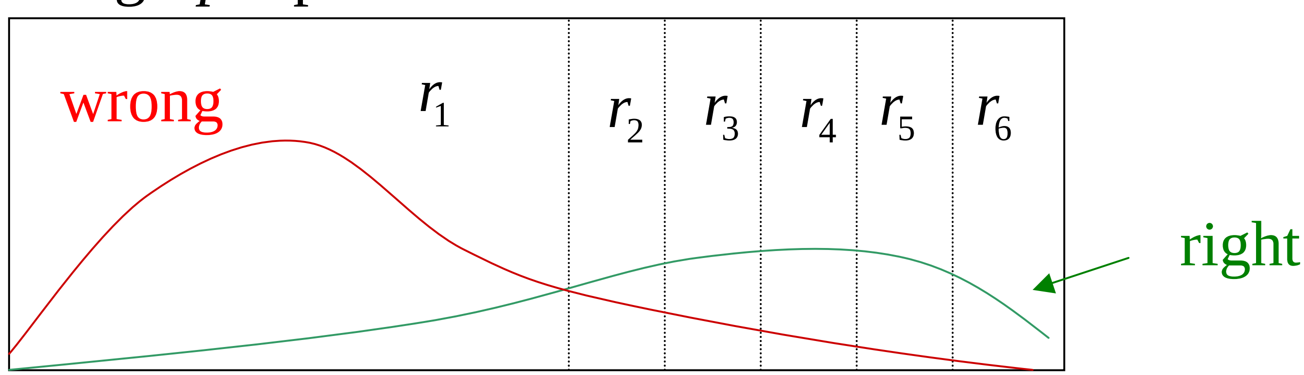
If we tag events wrongly, we'll measure CP violation as

$$p(B^0_{tagged} \to f_{CP}) \propto e^{-\Gamma t}\left[(1-w)(1-\sin 2\phi_1 \sin \Delta m \Delta t) + w(1+\sin 2\phi_1 \sin \Delta m \Delta t)\right]$$
$$= e^{-\Gamma t}\left[\{1-(1-2w)\sin 2\phi_1 \sin \Delta m \Delta t\}\right]$$

So the measurement is *diluted* by a factor $(1-2w) \equiv r$

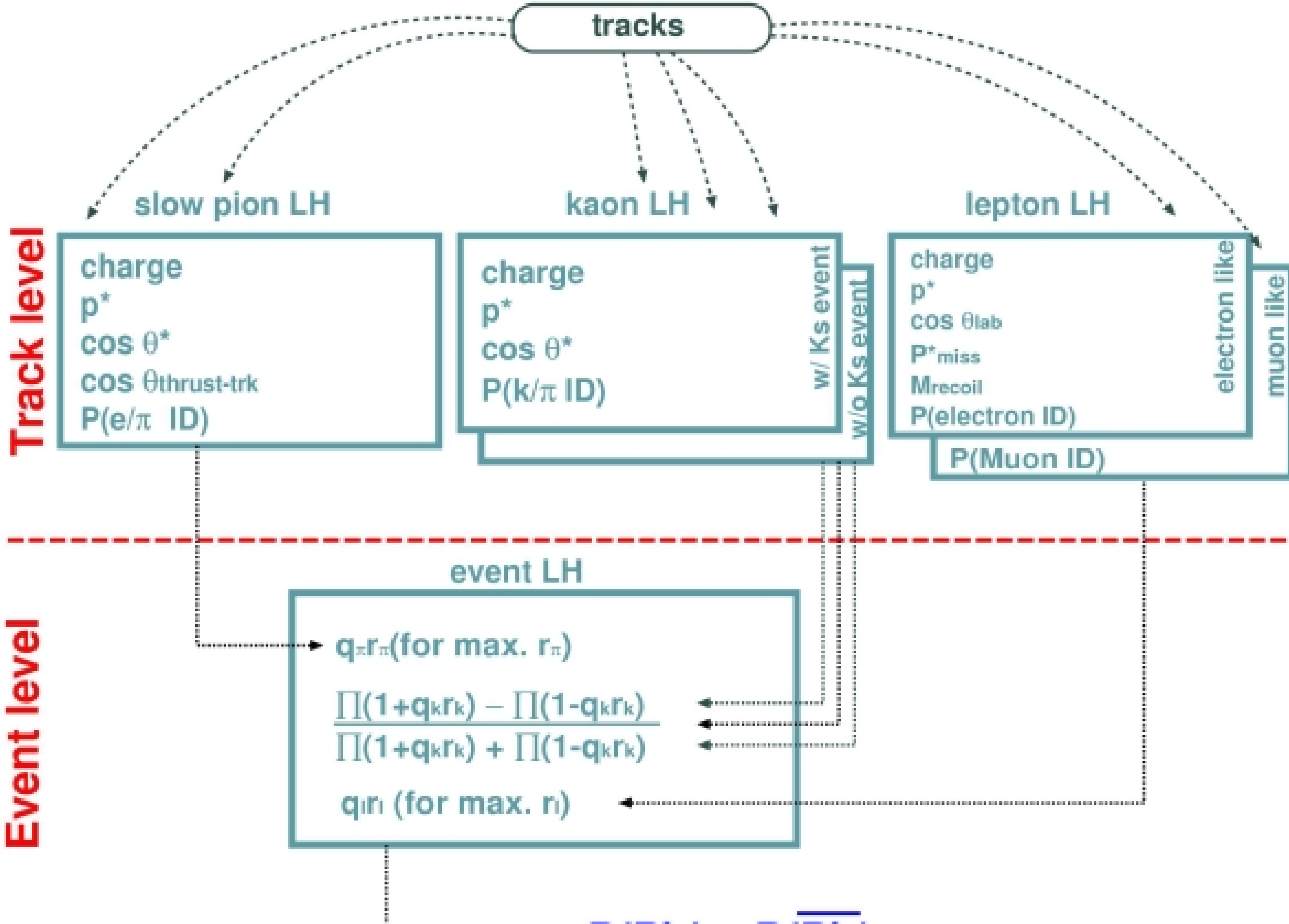
Ideally, we can determine this on an event by event basis to be used in the CP fit

Example, for high-*p* lepton



p^*

Multi-dimensional Flavor Tagging



$$q \cdot r \equiv P(B^0_{tag}) - P(\overline{B^0_{tag}})$$